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SENSITIVITY OF LIQUID MONOPROPELLANTS TO COMPRESSION IGNITION

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Safe start-up and operation of a liquid propellant gun system can be accomplished if the relevant sensitivity parameters or hazard parameters of the candidate monopropellant as relates to secondary ignition effects in the LPG environment can be identified and measured. Here we define secondary ignition as any propellant ignitions due to sources other than direct initiation. Flow factors, ignition reaction factors, pressure development, and confinement times all contribute in defining this regime of safe

operation of the liquid monopropellant system.

The secondary ignition event that we have focused on in this study is the collapse of a bubble under rapid compression of the liquid monopropellant charge. The particular propellant utilized in all tests was NOS-365.

In this study, Princeton Combustion Research Laboratories, Inc., has utilized its Compression Ignition Sensitivity Tester, with minor modifications, to produce on a systematic basis rapid compression of the liquid monopropellant charge with various rates of pressure rise, with various amounts of finely distributed ullage, with and without pre-pressurization of the propellant charge, to determine operating domains of safe start-up operation insofar as avoidance of compression ignition due to entrapped bubble collapse is concerned. Generally speaking, safe start-up without any sign of secondary ignition or runaway exothermic reaction due to compression ignition is obtainable by (a) elimination of all air in the system, a probably impractical requirement, (b) avoidance of sharp entry ports or other channel locations where cavitation may occur in the gun filling system, probably also an impractical requirement, (c) management of the rate of pressure rise in the liquid charge during start-up, a requirement that can be met by rational design of the ignition system, and (d) pre-pressurizing the charge of LP before the onset of the rapid pressure rise of the start-up. These four prescriptions define the domain of explosion-free start-up, on the basis of the LP compression ignition experiments performed by PCRL.

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SENSITIVITY OF LIQUID MONOPROPELLANTS TO COMPRESSION IGNITION*

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I. Introduction

Monopropellant liquid propellant gun (LPG) systems have been developed generally along two lines, the pre-loaded type (so-called bulk-loaded LPG) and the direct-injection type (so-called regenerative type). In each of these types, the liquid charge is brought rather rapidly up to gun operating pressure, ca. 30 to 60 kpsi, in a rise time on the order of 0.1 to 1 msec. Although hundreds of successful firings have been made with both types of gun, with several different types of liquid monopropellant, in sizes up to 4-inch barrels, occasional high pressure peaks and a few destructive explosions have taken place. This almost-successful test record suggests that the particular monopropellants selected are not themselves at fault, or high pressure peaks and explosions would have occurred with far greater frequency.

Safe start-up and operation of a liquid propellant gun system can be accomplished if the relevant sensitivity parameters or hazard parameters of the candidate monopropellant as relates to secondary ignition effects in the LPG environment can be identified and measured. Here we define secondary ignition as any propellant ignitions due to sources other than direct initiation. Flow factors, ignition reaction factors, pressure development, and confinement times all contribute in defining this regime of safe operation of the liquid monopropellant system.

The secondary ignition event that we have focused on in this study is the collapse of a bubble under rapid compression of the liquid monopropellant charge. The particular propellant utilized in all tests was NOS-365.

Test firings with experimental liquid propellant gun (LPG) systems during the past several years indicate that one of the concerns in practical application of LPG's is the possibility of unexpected high pressure peaks and/or explosion during start-up operation due to these secondary ignition sources, when pressure is applied rapidly to the liquid monopropellant in the chamber. One of the explanations that has emerged from the evidence available for secondary ignition in an LPG environment is that air bubbles due to excessive ullage in the firing chamber, brought in during the pre-firing fill process, become hot spots of unusual severity during the start-up as a result of rapid compression. Evidence further suggests that bubbles may not be air-filled but simply vapor-filled, formed by cavitation during the filling process.

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These occasional high pressure peaks in the liquid propellant (LP) charge during the ballistic firing of regenerative direct-injection LPG and LP fixtures have been experienced under conditions supposedly identical with those that produce satisfactory ballistic operation but with no evidence of high pressure peaks or regenerative piston reversal.[1] Because the possibility of high pressure peaks (anomolous p-t history in the liquid charge) is so strongly dependent on the start-up process and associated interaction between liquid propellant pressurization rate, residual ullage volume and degree of subdivision or distribution of bubbles in the LP charge, nature of the bubbles (permanent gas or liquid vapor) and liquid monopropellant sensitivity to compression ignition, and because the subsequent combustion cycle is critically dependent on the details of the interactions during the start-up phase, it is essential that a quantitative characterization of the threshold for runaway reaction associated with these secondary ignition sites be obtained and brought under precise control.

These secondary ignition events may not immediately generate significant pressure. Thus, sufficient propellant confinement time under pressure may be required to allow enough gas generation from the ignition event. If significant gas evolution is detected in a time which is much greater than the propellant confinement time in end-use application, then it can be safely concluded that gas evolution rate is so slow that the pressure generated by a particular secondary ignition event will be of no consequence to the system's designer. In large caliber gun applications, for instance, the propellant confinement time under pressure is typically on the order of 5 msec and, so, the detection of significant pressure associated with a secondary ignition event at times greater than 20 msec after the firing event (input stimulus) may be inconsequential insofar as practical development programs are concerned.

In this study, Princeton Combustion Research Laboratories Inc., has utilized its Compression Ignition Sensitivity Tester, with minor modifications, to produce on a systematic basis rapid compression of the liquid monopropellant charge with various rates of pressure rise, with various amounts of finely distributed ullage, with and without pre-pressurization of the propellant charge, to determine operating domains of safe start-up operation insofar as avoidance of compression ignition due to entrapped bubble collapse is concerned. Generally speaking, safe start-up without any sign of secondary ignition or runaway exothermic reaction due to compression ignition is obtainable by (a) elimination of all air in the system, a probably impractical requirement, (b) avoidance of sharp entry ports or other channel locations where cavitation may occur in the gun filling system, probably also an impractical requirement, (c) management of the rate of pressure rise in the liquid charge during start-up, a requirement that can be met by rational design of the ignition system, and (d) pre-pressurizing the charge of LP before the onset of the rapid pressure rise of the start-up. These four prescriptions define the domain of explosion-free start-up, on the basis of the LP compression ignition experiments performed by PCRL.

It should be noted, as a matter of practical interest, that in defining this domain of safe start-up, it was necessary to provoke explosions in the test apparatus. The domain of safe start-up is defined by the "dividing surface" between the conditions that produce explosion and those that never produce explosion. The apparatus was fitted in each case with a pressure-relief shear disc assembly, which always functioned properly. The most significant point of interest is that there was never any evidence of a destructive detonation, and that the apparatus was always re-usable after replacement of the pressure-relief shear disc. This experience supports the conclusions that have occurred in practical LP gun development programs, that no detonations have occurred.

Furthermore, prior to conducting compression ignition sensitivity studies of a pre-compressed, multiple bubble liquid monopropellant charge, flow visualization studies were conducted with a transparent chamber in order to define the physical state of the liquid propellant charge after rapid-load sequence, at the system "fire" condition.

In passing, we note that the problem of ullage in an explosive medium is not limited to the field of LP monopropellant gun systems. It can arise in LP monopropellant (e.g., hydrazine) power generating systems designed for aircraft and spacecraft use, and it can arise in the problem of premature warhead explosions due to setback acceleration of plastic-type warhead explosives in high velocity projectiles. Defining the safe domain of operation for explosive media containing bubbles is a task of general significance.

II. Flow Visualization Studies

The PCRL Compression Ignition Sensitivity Tester [2,3] incorporates features to control the rate of rapid loading of the liquid monopropellant charge, the volume percent of injected air ullage, the resulting break-up phenomenon of the bulk ullage into some mean bubble distribution through the charge, and the pre-pressurization level of the liquid propellant charge. The objective of the flow visualization phase of this project was to define the physical state of the liquid propellant charge after rapid load, at the system "fire" condition, by obtaining a photographic record of the resulting bubble distribution and a pressure record indicating liquid pre-pressurization level.

Figure 1 shows an assembly drawing of the Transparent Visualization Chamber and the Pneumatic Load Liquid Propellant (L.P.) Cylinder utilized in the flow visualization studies. The schematic drawing presented in Figure 2 identifies functional components such as valves, gas lines, liquid fill and discharge lines, and electrical connections. The Transparent Visualization Chamber was machined from a cast acrylic block with a 0.4375-inch diameter bore. The chamber is provided with an End Plug which carries the contact wire for actuation of an electronic strobe light. The Transparent Visualization Chamber also contains a Bleed Valve for flushing residual ullage from the system prior to rapid injection of the liquid propellant charge. A Kristal Type 601A pressure transducer is fitted into the chamber to monitor the pressure-time history of the rapid loading process and is located 0.70-inch downstream of the centerline of the injection port. The injection port is designed so as to accept various flow guides to alter the cavitation dynamics of the injected liquid. The chamber bore is fitted with a Separator Piston which seals the bore upstream of the injection port. A Projectile Piston is utilized to facilitate chamber filling under rapid loading and provides the trigger to actuate the electronic strobe light upon completion of propellant filling. The maximum stroke of the Projectile Piston is 2.7-inch, providing a maximum volumetric loading of liquid propellant of 0.41 cu. in. (6.65 cc).

The Pneumatic Load L.P. Cylinder is machined from 416 SS. The 0.5-inch diameter bore contains a Pneumatic Piston which transfers the liquid propellant charge through a Poppet Valve into the injection port of the Transparent Visualization Chamber. The Pneumatic Load L.P. Cylinder acts as a liquid syringe to control the rapid loading process. A regulated supply of N_2 gas fed through a Solenoid Valve provides the driving pressure for acceleration of the Pneumatic Piston. The injection time is controlled by this driving pressure, for a fixed volumetric loading of liquid propellant. The Poppet Valve controls the final liquid pre-pressurization level in the Transparent Visualization Chamber bore by adjustment of the Poppet Valve Spring compression. The Pneumatic Load L.P. Cylinder contains a Silicon Rubber Septum through which a Gas Ullage Syringe, i.e., hypodermic needle, passes to introduce a precise loading of air ullage (volume percent, STP). Liquid propellant is introduced into the Pneumatic Load L.P. Cylinder through a fill port.

The rapid load sequence is initiated by activating the circuit that opens the Solenoid Valve which releases the driving N_2 pressure into the Pneumatic Load L.P. Cylinder to accelerate the Pneumatic Piston. The motion of the Pneumatic Piston forces the liquid propellant and its gas ullage past the Poppet Valve once the force balance on the Poppet Valve Spring establishes Poppet Valve opening. The liquid propellant and its gas ullage flow through the Flow Guide in the injection port into the bore of the Transparent Visualization Chamber, possibly resulting in cavitation depending on the nature of the orifice. The Projectile Piston is then driven to the right allowing the charge to fill the bore until maximum stroke is achieved. The contact of the Projectile Piston with the contact wire in the End Plug activates a time delay relay circuit that controls the firing of the electronic strobe light. The purpose of the time delay circuit is to provide for a prescribed delay between completion of filling of the liquid propellant in the chamber bore and system "fire". Thus, sufficient time can be provided between rapid load and system "fire" to allow for the collapse of bubbles in the liquid charge (cavitation bubbles return to solution) and to provide an initial condition of a pre-pressurized liquid charge at the time of system "fire". The time delay relay circuit has the capability of adjusting the time delay in 1 msec increments in the range $1 < t(\text{msec}) < 100$.

Figure 3 displays a composite photograph of rapid load tests of NOS-365 liquid monopropellant charge illustrating the physical condition of the charge in the Transparent Visualization Chamber bore at the instant of system "fire", i.e., at t = 10 msec after Projectile Piston contact with End Plug, for two extreme conditions of volumetric air ullage loading. These correspond to (a) neat propellant - 0% ullage, and (b) 3.1% volumetric air ullage, respectively. The line (injection) pressure is 500 psig. This can be compared with the composite photograph shown in Figure 4, taken at the instant of Projectile Piston contact with End Plug, i.e., no time delay, for (a) 0%, (b) 0.9%, and (c) 3.1% volumetric air ullage loading at the same line (injection) pressure of 500 psig. Several important observations are noted. From Figure 4a, neat propellant rapid fill tests with $t_{delay} = 0$ show cavitation bubbles distributed throughout the charge. For this system "fire" condition, the pressure wave generated at the extreme right end of the liquid column by the slamming of the Projectile Piston against the the End Plug has not yet propagated upstream to the location of the injection port. From the original high contrast photographs it was determined that the mean cavitation bubble diameter was approximately 0.004-inch. However, by providing a 10 msec delay prior to system "fire", the results of Figure 3a for 0% ullage indicate that the passage of the "water hammer" wave through the propellant charge causes the cavitation bubbles to return to solution. The cavitation bubbles which were introduced into the liquid propellant charge during rapid load through the injection port have collapsed. This is an important observation. It implies that the number of bubble sites that could act as centers for ignition during rapid compressive loading of the liquid propellant charge are considerably reduced when sufficient time is provided for the cavitation bubbles to return to solution.

Hence, it is conjectured, and it is demonstrated in actual testing, that the sensitivity of the neat liquid propellant charge to compression ignition is significantly reduced. Furthermore, as shown in the oscillograph traces of Figure 5a, at the system "fire" condition, i.e., t = 10 msec delay, the liquid propellant charge is pre-pressurized to approximately 350 psig. For a zero time delay no pre-pressurization of the liquid charge results. Thus, by providing a 10 msec delay, the initial condition at system "fire" is that of a pre-pressurized neat propellant charge. The sensitivity of such a pre-pressurized neat propellant charge to compression ignition is felt to be reduced from that in which no pre-pressurization of the liquid charge occurs. This is discussed further in the following section.

Figure 3b depicts the physical condition of the rapid load liquid propellant charge with 3.1% volumetric air ullage at t_{delay} = 10 msec and a line (injection) pressure of 500 psig. A "fog-like" appearance of the propellant charge with mean bubble diameter considerably less than 0.001-inch distributed through the charge is obtained. This is to be compared with Figure 4c for t_{delay} = 0. The "fog-like" appearance is more opaque, indicating larger bubbles than the case described above, and again, the mean bubble diameter is less than 0.001-inch, corresponding to the maximum resolution of the measurement technique. The smaller bubbles obtained in visualization tests of Figure 3b compared to those of Figure 4c are, again, a consequence of the passage of the "water hammer" wave through the charge, compressing the bubbles. Also, as shown in the oscillograph record of Figure 5b, at the system "fire" condition, i.e., t = 10 msec delay, the liquid propellant charge with 3.1% volumetric air loading is pre-pressurized to approximately 330 psig.

It is conjectured that the rapid load liquid propellant charge shown in Figure 3b is less sensitive to compression ignition than the similar rapid load liquid propellant charge of Figure 4c, due to smaller bubbles distributed through a pre-pressurized charge. This will be discussed further in the following section.

We anticipate that bubble size can be controlled by adjusting the line (injection) pressure and hence the time of injection associated with the Pneumatic Load L.P. Cylinder. We expect that bubbles of finer or coarser diameter can be established by choosing either faster or slower fill times, i.e., higher or lower line (injection) pressure. Additional series of flow visualization tests were conducted with NOS-365 liquid monopropellant at line (injection) pressures of 300 psig and 150 psig. Figure 6 displays a composite photograph of rapid load tests of NOS-365 liquid monopropellant illustrating the physical state of the charge in the Visualization Chamber bore at t_{delay} = 10 msec for a line (injection) pressure of 300 psig for (a) neat propellant - 0% ullage, and (b) 3.1% volumetric air ullage, respectively. These flow visualization results are qualitatively similar to those obtained in Figure 3 for 500 psig

line (injection) pressure. Analysis of the pressure-time trace of Figure 8a for neat propellant loading indicates that the pre-pressurization level of the liquid propellant charge at system "fire",i.e., t = 10 msec delay, is approximately 200 psig. These visualization studies should be compared with those obtained with t_{delay} = 0 msec, depicted in Figure 7. In Figure 7a for neat propellant, cavitation bubbles are seen distributed through the charge with intense injection activity at the location of the injection port. These cavitation bubbles are not evident in Figure 6a in which system "fire" is delayed by 10 msec. The cavitation bubbles which were introduced during rapid load through the fill port have collapsed upon passage of the "water hammer" wave past the injection port. Thus, for the case of 10 msec time delay before system "fire", the state of the neat liquid charge upon rapid loading is qualitatively the same for 500 psig and 300 psig line pressure, except that a higher pre-pressurization level is achieved for the higher injection pressure.

Figure 6b depicts the physical state of the rapid load liquid propellant charge with 3.1% volumetric air loading at t_{delay} = 10 msec and an injection pressure of 300 psig. Again, the characteristic "fog-like" appearance of the propellant charge is observed with mean bubble diameter of less than 0.001-inch distributed through the charge (maximum resolution of measurement technique). Comparing this with Figure 7c, obtained with t_{delay} = 0, we find that the "fog-like" appearance is more opaque indicating larger bubbles than those in Figure 6b for t_{delay} = 10 msec. Also, as shown in the oscillograph record of Figure 8b, at the system "fire" condition of t = 10 msec, the liquid propellant charge with 3.1% volumetric air loading is pre-pressurized to 175 psig. No pre-pressurization of the liquid charge is achieved with zero delay time.

Finally, Figure 9 displays a composite photograph of rapid load tests illustrating the physical state of the propellant charge in the Visualization Chamber bore at 10 msec delay for an injection pressure of 150 psig for (a) neat propellant - 0% ullage, and (b) 3.1% volumetric air ullage, respectively.

For neat propellant loading, Figure 9a, the charge is essentially bubble free, the cavitation phenomenon being significantly less severe at low driving pressure. As shown in the oscillograph record of Figure 11a, the pre-pressurization level of the liquid propellant charge at system "fire",i.e., t = 10 msec delay, is 125 psig. For 3.1% volumetric air ullage, Figure 9b, fine bubbles with mean diameter less than 0.001-inch are seen distributed through the liquid propellant. The pre-pressurization level at system "fire" is 120 psig, as determined from the p-t trace of Figure 11b. These flow visualization tests are dramatically different from those shown in Figure 10, for t_{delay} = 0. Figure 10a, the 0% ullage case, shows a liquid column relatively free of bubbles, indicating that the cavitation phenomenon is greatly reduced at this low

injection pressure, even though the "water hammer" wave has not yet propagated through the charge (t_{delay} = 0). Some large diameter bubbles can be seen in the center of the column. Bubbles with diameter as large as 0.023-inch can be observed. The effect of the low injection pressure on ullage break-up is more pronounced in Figure 10b, the 0.9% ullage case. Large diameter bubbles and even undivided ullage can be seen superimposed on a field of well dispersed bubbles of mean diameter 0.009-inch. Bubbles with diameter as large as 0.045-inch can be seen in the column. Note that the "fog-like" quality of the liquid column observed in higher injection pressure tests, i.e., 500 psig and 300 psig, and 0.9% ullage with zero time delay for system "fire" is not observed at this lower injection pressure. The subdivision of the original ullage loading in the flow guide and injector port is not as intense at low injection pressure. The same observation is borne out for the 3.1% ullage case, shown in Figure 10c. The mean bubble diameter for this case is 0.006-inch, with bubbles well-distributed through the charge. The "fog-like" opaque appearance of the charge as observed for the 3.1% ullage case at t_{delay} = 0 msec for 500 psig and 300 psig injection pressure is not observed at 150 psig injection pressure.

Table 1 summarizes the results of flow visualization studies conducted with NOS-365 liquid monopropellant at a system "fire" condition at t = 10 msec after Projectile Piston contact with the End Plug in the Visualization Chamber bore. This is to be compared with Table 2 for system "fire" at t = 0 msec.

We summarize the results of the flow visualization studies as follows:

1. Rapid fill tests performed with the Pneumatic Load L.P. Cylinder and Visualization Chamber (a transparent version of the Liquid Propellant Compression Chamber used in compression ignition sensitivity studies) produce various reproducible physical states of the NOS-365 liquid propellant charge. A pre-compressed, pre-pressurized, multiple bubble NOS-365 medium, representing initial conditions found in other liquid propellant gun studies, has been achieved.

2. The versatility of the rapid-load system has been established. Parameters under precise control are liquid propellant pre-pressurization level, volume percent of injected ullage and mean bubble size in the rapid-load propellant charge. Although not a parameter in the present series of tests, the type of occluded gas can be varied.

3. The physical state of the NOS-365 liquid monopropellant charge with entrapped ullage after rapid-load into the Visualization Chamber bore is dramatically different for a pre-compressed, pre-pressurized charge than for one that is not. In general, we find that smaller bubbles are distributed throughout the propellant charge when a sufficient time delay has elapsed prior to system "fire", due to the passage of compression waves through the charge.

4. The formation of bubbles in a rapid-load neat propellant charge appears to result from cavitation effects in the liquid propellant flow guide and injection port. It is estimated that the resulting void volume may be as much as 0.1% of the total available chamber bore volume. At the system "fire" condition of t = 0 msec, it is clearly demonstrated that cavitation bubbles have not returned to solution and the liquid pressure is still atmospheric. At the system "fire" condition of t = 10 msec, compression waves from the "water hammer" effect have propagated through the propellant charge, and the cavitation bubbles have collapsed and returned to solution. The initial condition, i.e., the system "fire" condition, is that of a pre-pressurized liquid propellant charge.

5. Since the number of bubble sites that could act as centers for ignition during rapid compressive loading of the liquid propellant charge are considerably reduced when sufficient time is provided for cavitation bubbles to return to solution and residual air bubbles to be collapsed due to the passage of compression waves through the charge associated with the "water hammer" effect, it is conjectured that the sensitivity of such a propellant charge is considerably reduced. This compression ignition sensitivity is discussed in the following section.

III. Compression Ignition Sensitivity Tests

In order to establish the threshold conditions for runaway reaction in the NOS-365 liquid monopropellant charge with entrapped bubbles due to secondary ignition of the propellant associated with rapid compression, attention was directed to the precise control of the pressurization rate to which the rapidly-loaded charge is subjected. Previous studies performed by Princeton Combustion Research Laboratories Inc., References 2 through 6, indicated that for a given peak pressure in the liquid, the liquid pressurization rate is an important parameter in determining sensitivity to compression ignition. Figure 12 shows an assembly drawing of the L.P. Compression Ignition Sensitivity Tester used in the experimental studies. Functional components such as valves, gas lines, liquid fill and discharge lines, gas vent, and electrical connections are presented in the schematic drawing, Figure 13. Following the complete assembly of the L.P. Compression Chamber and the Pneumatic Load L.P. Cylinder, the Starter Charge Chamber is fitted with an electric primer and loaded with the prescribed smokeless powder mix. The Starter Charge Chamber and the L.P. Compression Chamber are then joined together with the Chamber Coupling Collar on the test stand. The liquid propellant filling procedure can then begin. This is described in detail in Reference 2. The rapid-load sequence in the L.P. Compression Chamber is similar to that described above for the rapid-load sequence in the Transparent Visualization Chamber.

In previous PCRL compression ignition studies of Reference 2, we found that the liquid propellant pressure-time history could be controlled by varying the type of smokeless powder charge in the Starter Charge Chamber to which the Separator Piston, separating pressurizing chamber and liquid propellant, is subjected. However, certain deficiencies were noted in the design of the Compression Ignition Sensitivity Tester of Reference 2. One of the objectives of this study was to eliminate those deficiencies so that any ambiguities in interpreting results could be reduced, if not eliminated.

The first area of concern was the elimination of the large amplitude oscillations appearing in the liquid pressure-time history. The peak-to-peak variation of some of these oscillations was as large as 40 kpsi, some pressure excursions even indicating tension in the liquid. The implication of resulting cavitation in the liquid due to local "negative pressure" effects in the liquid, and the effect of the large instantaneous pressurization and depressurization rates in the liquid on the tendency to compression ignition needed to be addressed. A representative pressure-time trace taken from the previous firing tests of inert simulant of Reference 2 is shown in Figure 15a. This was obtained with Starter Charge TYPE E (see Table 3) and neat liquid simulant. Pressure transducer P1 is located in the L.P. Compression Chamber 0.60-inch from the rear face of the Separator Piston. The vertical scale is 20 kpsi/div, with shifted baselines for each pressure record. Evident in these p-t traces are the pressure oscillations with oscillation frequency of approximately 5000 Hz. The liquid

response to the driving pressure, p_c, generated in the Starter Charge Chamber is essentially a damped spring-mass system. The liquid responds to a forcing function with oscillation frequency corresponding to the fundamental longitudinal acoustic mode of the Starter Charge Chamber. It was determined that the oscillation amplitude in the liquid could be reduced by re-design of the Blast Shield containing the gas communication ports between Starter Charge Chamber and Separator Piston in the L.P. Compression Chamber bore. In this re-design, a conical-shaped Blast Shield was employed with these gas communication ports located at the mid-length position of the Starter Charge Chamber, essentially at a pressure antimode for the chamber fundamental longitudinal mode. The Δp excursion about the mean chamber pressure is least at this axial position in the Starter Charge Chamber.

Another design change in the Compression Ignition Sensitivity Tester involved the Separator Piston. Extreme care was taken in the re-design to ensure that the liquid propellant charge is isolated from the hot combustion gases of the solid propellant starter charge which drives the Separator Piston, thereby compressing the liquid propellant and its associated ullage. Should an ignition event in the liquid propellant be observed, it is important to be able to isolate the cause as being compression ignition alone. The previously utilized Separator Piston was a composite piston made of aluminum and nylon. At high pressure the nylon portion expanded radially outward to the internal diameter of the L.P. Compression Chamber bore to prevent gas leakage from Starter Charge Chamber to liquid propellant charge. This was designed purposefully as a high pressure seal. "O"-rings were incorporated for low pressure sealing. However, if "O"-ring failure occurred, there was no assurance that hot gas leakage into the liquid propellant did not occur. The new modified Separator Piston is machined from 7075-T651 aluminum in the shape of a "dumbbell". A water buffer is introduced in the annular region between head and rear of the dumbbell by use of a hypodermic needle during the pre-fill procedure. Both head and rear of the dumbbell are fitted with "O"-ring seals. Thus, should "O"-ring seal failure occur, the water buffer serves the purpose of quenching any hot particles or hot gas that may have leaked past the seal. The re-designed conical Blast Shield and dumbbell-shaped Separator Piston are shown in the assembly drawing of Figure 12. With these design changes it is reasonable to expect that liquid pressure oscillations would be reduced and that, should the liquid propellant charge undergo runaway reaction at some point in the compression cycle, the cause can be attributed to hot spot initiation resulting from bubble collapse, i.e., compression ignition.

A comparison of pressure-time histories for inert simulant tests prior to and after these modifications are shown in Figures 14 and 15. In these inert simulant tests the line (injection) pressure to the Pneumatic Load L.P. Cylinder was 500 psig, neat water was dynamically-loaded in the Compression Chamber, and two different pressurization p-t start-up curves were employed. Figure 14 corresponds to TYPE C start-up curve

(p_c) and Figure 15 corresponds to TYPE E start-up curve (p_c). In all cases a mean peak liquid pressure of 25 kpsi is achieved. These figures display digitized firing records of the pressure-time history in the Starter Charge Chamber, $p_c(t)$, and in the bore of the L.P. Compression Chamber, $p_1(t)$. The vertical scale is 20 kpsi/div, with shifted baselines for each pressure record. In Figures 14a and 15a, corresponding to previous inert simulant tests, we note the characteristic 5000 Hz oscillation in the p_c-t record, associated with excitation of the fundamental longitudinal acoustic mode of the Starter Charge Chamber due to the coupling with the combustion process. The liquid response, $p_1(t)$, displays large scale oscillations. Figures 14b and 15b correspond to inert simulant tests after system modification. The liquid response, $p_1(t)$, for TYPE C and TYPE E starter charges is relatively smooth. Inspection of the Separator Piston after system test revealed no evidence of gas leakage past the piston.

Table 4 summarizes the compression ignition sensitivity tests performed during this study. In all cases the initial condition at system "fire" is that of a pre-pressurized liquid charge, corresponding to t_{delay} = 10 msec. One or more repeats of each test were performed to ensure consistency of results. Parameters which were varied in this test matrix were: (i) the start-up pressurization curve, either TYPE C, D, or E; (ii) the volume percent of injected air ullage, either neat propellant or 3.1% ullage; and (iii) the injection pressure of the liquid propellant for rapid load. The achievable liquid pressurization rates for each of these starter charges is given in Table 3. In those cases where small scale oscillations are present in the p-t history, the liquid pressurization rate is obtained by drawing a mean through the pressure oscillations up to the operating pressure of 25 kpsi. The most rapid pressurization rate is obtained with 6.80g <u>Herco</u> Pistol Powder in the main Starter Charge Chamber and 1.30g <u>Dupont</u> IMR 4198 fuse (TYPE E), 70 kpsi/msec. The slowest mean pressurization rate is obtained with 2.60 g IMR fuse and 6.50 g IMR main starter charge (TYPE C), 25 kpsi/msec.

Figures 16 through 27 display digitized firing records of the sensitivity tests performed for ten different sets of conditions. In each case liquid propellant pressure-time histories p_1 (t) and p_3 (t) are displayed with shifted baselines. The vertical scaling is 20 kpsi/div. Pressure transducer P3 is located 2.00 inch downstream of pressure transducer P1. The horizontal scaling is 1 msec/div in those tests were a benign response occurred and 2 msec/div in those tests where explosive response occurs. Also displayed is the timewise response of PCRL Phototransistor Light Sensor Assemblies, located 180 degrees circumferentially from the pressure transducer locations in the L.P. Compression Chamber. For all benign responses of the liquid monopropellant, the light sensor responses, LS1 and LS3, remain at their respective baselines. Only when an explosive response of the liquid monopropellant occurs can we see a departure of the light sensor responses from baseline.

All firing tests performed with neat monopropellant resulted in a benign response of the propellant for the range of pressurization rates considered: $25 \leq dp_L/dt$ [kpsi/msec] ≤ 70. This is an important observation. In previous tests, Table 5 indicates that an explosive response of neat propellant could ensue in some instances. The reasons for the decreased sensitivity of neat propellant in the present test series are two-fold. The cavitation phenomenon has been greatly reduced because of the elimination of possible "negative pressure" effects in the liquid, arising from the large scale oscillatory behavior in the liquid. Secondly, cavitation bubbles that may arise during the rapid-load procedure have either returned to solution or have been pre-compressed by allowing for passage of compression waves ("water hammer") through the charge prior to system fire, i.e., a time delay before system fire. Thus the initial condition at system fire is a pre-pressurized liquid charge. The number of possible ignition centers is greatly reduced and the diameter of residual bubbles at system fire is dramatically reduced. This physical state of the liquid charge has been discussed in detail in the results of the flow visualization studies. A comparison of two neat propellant firing tests with TYPE D start-up curve is shown in Figure 28. Figure 28a was obtained with the unmodified system and no pre-pressurization of the liquid at system fire. Ignition of the charge results, causing an explosive response of the liquid at approximately 1.5 msec after the onset of rapid pressurization in the liquid. A pressure spike of approximately 80 kpsi is achieved, followed by depressurization of the L.P. Compression Chamber bore associated with Shear Disc failure. Figure 28b was obtained with the modified system and a liquid pressure at system fire of 350 psig. The liquid response, $p_1(t)$ and $p_3(t)$, is benign.

Of the twenty-six compression ignition tests performed with a pre-pressurized liquid charge (see Table 4 for pre-pressurization level) only five resulted in an explosive response of the liquid monopropellant. Three of these occurred at 3.1% volumetric air ullage loading, an injection pressure of 300 psig (pre-pressurization of 175 psig), and TYPE D starter charge. One test at these same conditions resulted in a benign response of the liquid monopropellant. The firing records for two of the explosive responses, RUN 17 and RUN 18, are shown in Figures 23 and 24, respectively. The firing record for the benign response, RUN 16, is shown in Figure 22. It is interesting to note that the liquid pressurization start-up is practically identical in RUNS 16 and 17, yet RUN 17 shows a delayed runaway reaction approximately 8.4 msec after pressurization start-up. Similarly, RUN 18 shows delayed runaway reaction approximately 12.0 msec after pressurization start-up. Although the firing record is not displayed, RUN 15 resulted in delayed runaway reaction at $t > 5.0$ msec after pressurization start-up. Unfortunately the data recording window in RUN 15 was too narrow to capture the entire event, so the precise time of runaway reaction is not known. Not only do the pressure records of RUNS 17 and 18 indicate delayed runaway reaction, but the light sensors, located at the same axial locations as the pressure transducers, indicate delayed runaway reaction

insofar as detection of visible and near-infrared radiation associated with combustion is concerned.

Two other explosive responses occurred at 3.1% volumetric air ullage loading, an injection pressure of 300 psig (pre-pressurization of 175 psig), and TYPE E starter charge. One test at these conditions resulted in a benign response of the liquid monopropellant. The firing record for one of the explosive responses, RUN 26, is shown in Figure 27. The firing record for the benign response, RUN 27, is shown in Figure 26. Again we note the delayed runaway reaction at t = 12.0 msec after pressurization start-up, as detected by the pressure transducers and light sensor LS3. Apparently light sensor LS1 was not functioning properly because of a cracked sapphire window in the light sensor housing.

IV. Discussion and Conclusions

In determining whether rapid compression of a liquid monopropellant charge with associated distributed bubbles can lead to secondary ignition sites (hot spot ignition) and resulting explosion of the charge, we have performed a series of sensitivity tests with the modified PCRL Compression Ignition Sensitivity Tester. We have summarized the results of these tests in the three-dimensional plot of Figure 29. The axes correspond to the critical parameters that were varied in the test matrix: (i) the liquid pressurization rate (kpsi/msec); (ii) the volumetric air ullage loading, either zero (neat propellant) or 3.1% (0.013 in^3 distributed air ullage with mean bubble diameter less than 0.001 in); and (iii) the liquid propellant injection pressure (psig). The liquid propellant injection pressure is an important parameter for several reasons. From a fluid mechanical point of view, the injection pressure determines the flow velocity and, for a given injector orifice geometry, thereby determines the cavitation phenomenon. Secondly, the degree of subdivision of the initial bulk ullage upon rapid load depends on the rate of propellant injection. Lastly, the equilibrium pressure in the liquid charge at the system fire condition, i.e., pre-pressurization level, is dependent on the injection pressure, as seen in Table 1. The liquid pre-pressurization levels (p_o) are given in Figure 29 in parentheses. Thus, for instance, at an injection pressure of 300 psig and 3.1% volumetric air ullage loading, the liquid pre-pressurization level is 175 psig.

We have found that the response of a pre-pressurized neat NOS-365 liquid monopropellant charge to pressurization rates (dp/dt) $\leq$ 70 kpsi/msec is always benign. This is true for injection pressures of 300 and 500 psig, corresponding to liquid pre-pressurization levels of 200 and 350 psig, respectively. We might also venture to say that we expect that all points lying in the "neat" propellant plane with injection pressure greater than 500 psig, (dp/dt) $\leq$ 70 kpsi/msec, and a time delay before system fire would also be benign, even though no sensitivity tests were performed. This is because the higher the injection pressure, the smaller any residual bubbles that may be distributed through the charge and the higher the pre-pressurization level. Hence, decreased sensitivity to compression ignition would be anticipated.

We have seen previously, in Reference 2, that "neat" propellant which is not pre-pressurized at system fire can undergo compression ignition and ensuing explosion. If severe cavitation occurs in the propellant during rapid fill and insufficient time exists for the cavitation bubbles to return to solution prior to system fire (associated with traverse of compression waves in the liquid), then ignition and explosion may ensue for a rapid enough compression. The cavitation bubbles which have not collapsed and, thus, have not returned to solution can serve as centers for hot spot development and compression ignition.

The only tests in the present study in which runaway reaction of the liquid monopropellant was observed was when gas ullage was purposefully introduced into the liquid charge prior to rapid load. The response of a pre-pressurized NOS-365 liquid monopropellant charge (p_o = 175 psig) with 3.1% air ullage (0.013 in^3 distributed air ullage with mean bubble diameter less than 0.001 in) is benign for compression rates (dp/dt) $\leq$ 25 kpsi/msec. However, as the rate increases the tendency toward initiating a reaction due to compression ignition increases. For (dp/dt) $\geq$ 45 kpsi/msec, explosions have been observed. It is apparent from the data records that runaway reaction of the pre-pressurized liquid monopropellant charge does not occur during rapid pressurization of the liquid but, rather, some time later. This suggests that establishing the interrelationship of pressurization time, bubble collapse time, heat retention (escape) time, and kinetic time scales (finite rate chemistry) is key to understanding the role of compression ignition as a secondary ignition source. It is speculated that the presence of a bubble(s) is not a sufficient condition for secondary ignition due to hot spot development associated with bubble collapse. That is, if the field pressure in the liquid after rapid pressurization is not sustained for a sufficient time, secondary ignition due to bubble collapse may not be able to be sustained. This suggests that runaway reaction in the liquid propellant may require an induction time. This is evidenced in the present series of compression ignition tests of a pre-pressurized liquid in which runaway reaction always occurred well after the rapid pressurization of the liquid charge, ca. 8-12 msec after rapid pressurization. The characteristic time scale analysis performed by PCRL in References 2 and 7 supports this hypothesis.

In considering whether rapid compression of a pre-pressurized liquid monopropellant charge with associated distributed bubbles can lead to secondary ignition sites (hot-spot ignition) and resulting explosion of the charge, we have to consider the detailed processes that may initiate a runaway exothermic chemical decomposition reaction. Heat produced by the compression process in the neighborhood of a collapsing bubble is believed to be the triggering agent, not the pressure itself. With one or more small bubbles in the liquid, a "hot spot" can be generated by the adiabatic compression of the bubble, either air or vapor, and if the bubble is initially large enough and if the compression process is rapid enough, the sharp local rise in temperature can cause the bubble to retain its heat long enough to initiate exothermic chemical reaction.

Thus the interesting features of the problem arise from consideration of the time scales inherent in the problem. Five have been identified in our previous research of Reference 2 and 7: (1) The induction time for chemical reaction in the vapor phase; (2) The corresponding chemical reaction time in the liquid phase; (3) The duration of heat retention in the bubble (heat conduction time); (4) The rise time of the imposed pressure "ramp"; (5) The collapse time of the bubble in response to the imposed pressure field. We restate the conclusions of that analysis here. If the chemical reaction induction time is long

compared with the heat retention time, (i.e., slow kinetics and tiny bubbles), there is a good chance that the runaway reaction can be avoided. Consideration of the relative times of bubble collapse and pressure rise has a very important bearing on the problem of explosion avoidance. It has been shown theoretically that the collapse time of a typical bubble, for the driving pressures considered, is only on the order of a few microseconds. On the other hand, realistic pressure rise times (an LPG system or a warhead explosive subjected to setback forces) are generally on the order of one or more milliseconds. Thus, there are hundreds and perhaps thousands of cycles of bubble collapse, rebound, and collapse again within the rise time. The heat retention time is generally also long compared with the collapse time. This means that each successive collapse introduces more and more compression heat into the bubble and in the immediately surrounding liquid, so that the danger point for runaway reaction would be well along in the rise of pressure, perhaps well after the applied pressure has reached the highest level. The results of these compression ignition tests support this theory.

Again, returning to Figure 29, the response of a rapid-load pre-pressurized NOS-365 liquid monopropellant charge (p_o = 330 psig) with 3.1% volumetric air ullage (0.013 in^3 distributed air ullage with mean bubble diameter less than 0.001 in) is benign for all compression rates considered, (dp/dt) $\leq$ 70 kpsi/msec. This is not surprising when compared with the results for 300 psig injection pressure (liquid pre-pressurization of 175 psig) and 3.1% volumetric air ullage loading, because the liquid pre-pressurization level is considerably higher and the fineness of the bubble distribution in the charge is expected to be greater (the resolution of the photographic technique employed in flow visualization studies is limited to 0.001 in). Thus, the sensitivity of the liquid monopropellant to compression ignition in the plane corresponding to 500 psig injection pressure should be decreased from that associated with the plane corresponding to 300 psig injection pressure, and this is seen to be the case.

This three-dimensional presentation of the experimental results indicates that a bounding surface exists separating benign response from explosive response of the liquid monopropellant in the simulated LPG environment under which the tests were performed. The gas generation resulting from a secondary ignition event can lead to rupture of a gun chamber or to a gun breech blow if it is rapid enough or if the volume expansion does not accommodate the gas production. In a regenerative LPG we have seen how, in some instances, a secondary ignition event in the liquid propellant reservoir can be accommodated because of volume expansion associated with regenerative piston reversal.[1]

The compression ignition events observed in this study do not immediately generate significant pressure. Thus, sufficient propellant confinement time under pressure is required to allow enough gas generation from the ignition event to result in

runaway reaction. In the Introduction it was stated that if significant gas evolution is detected from a compression ignition event under simulated gun conditions in a time which is much greater than the propellant confinement time in end-use application, then it may be concluded that gas evolution rate is so slow that the pressure generated by a particular secondary ignition event will be of little consequence to the system's designer. It is speculated that if the PCRL Compression Ignition Sensitivity Tester were designed to provide a propellant confinement time under pressure of only 3 - 5 msec, for example, the observation of an explosive response of the pre-pressurized liquid monopropellant with purposefully introduced ullage would be unlikely for the range of test parameters considered. In large caliber gun applications in which the propellant confinement time under pressure is typically 5 msec, runaway reaction from a secondary ignition event which requires 8 - 12 msec of confinement time under pressure may be inconsequential insofar as the practical LPG is concerned. However, since cavitation phenomena, wave phenomena, and residual air ullage in the system prior to rapid load are so system dependent and play such a critical role in safe start-up and operation of the LPG, one should not overlook the possibility of compression ignition. The existence of a domain of safe start-up and operation is quite important from the standpoint of practical LPG design and development programs. It appears that practical LPG design can proceed with confidence inasmuch as secondary ignition of the liquid monopropellant associated with bubble collapse can be circumvented by judicious design. It appears that the concept of liquid pre-pressurization prior to system fire can be worked into a practical LPG design by utilizing similar rapid fill procedures and timing delay circuitry concepts adopted for the Compression Ignition Sensitivity Tester. We have demonstrated how management of the liquid start-up pressurization history is so important for practical LPG applications, insofar as compression ignition sensitivity is concerned.

TABLE I. TABULATION OF RESULTS OF FLOW VISUALIZATION STUDIES CONDUCTED WITH NOS-365 LIQUID MONOPROPELLANT. THE SYSTEM "FIRE" CONDITION IS SET AT 10 msec AFTER "WATER HAMMER" SPIKE.

RUN NO.	LINE (INJECTION) PRESSURE (psig)	ULLAGE (VOLUME %, STP)	P_{spike} (psig)	P_{fire} (psig)	d_{mean} (in)
03	500	neat	1000	350	--
04	500	3.1	1000	330	<0.001
08	300	neat	500	200	--
07	300	3.1	500	175	<0.001
11	150	neat	250	125	--
14	150	3.1	170	120	<0.001

Note: The scale factor employed in obtaining the mean bubble diameter in the visualization photographs is obtained by noting that the Kristal Type 601A pressure transducer port threads are machined 3/8-24, i.e., a thread spacing of 0.0417 in.

TABLE 2. TABULATION OF RESULTS OF FLOW VISUALIZATION STUDIES CONDUCTED PREVIOUSLY WITH NOS-365 LIQUID MONOPROPELLANT. THE SYSTEM "FIRE" CONDITION IS SET AT ZERO TIME DELAY.

RUN NO.	LINE (INJECTION) PRESSURE (psig)	ULLAGE (VOLUME %, STP)	P_{spike} (psig)	d_{mean} (in)
20	500	neat	1100	0.004
27	500	3.1	900	<0.001
11	300	neat	540	0.008
14	300	3.1	540	<0.001
30	150	neat	130	0.023
37	150	3.1	220	0.006

TABLE 3. STARTER CHARGE LOADINGS AND ASSOCIATED LIQUID PRESSURIZATION RATES

TYPE	FUSE SECTION	MAIN CHAMBER	dp_L/dt (kpsi/msec)
C	2.60g DuPont IMR 4198	6.50g DuPont IMR 4198	35
D	1.30g DuPont IMR 4198	7.00g Herco Shotgun	4[illegible]
E	1.30g DuPont IMR 4198	6.80g Herco Pistol	70

TABLE 4. TABULATION OF COMPRESSION IGNITION SENSITIVITY TESTS WITH RAPID-LOAD NOS-365 LIQUID MONOPROPELLANT CHARGE. ALL TESTS PERFORMED WITH MODIFIED APPARATUS AND t_{DELAY} = 10 msec.

RUN NO.	START-UP CURVE	PERCENT ULLAGE (VOLUME)	INJECTION PRESSURE (psig)	LIQUID PRESSURE AT "FIRE" (psig)	SYSTEM RESPONSE
LP01	C	neat	500	350	benign
LP02	C	neat	500	350	benign
LP03	C	neat	300	200	benign
LP04	C	neat	300	200	benign
LP05	C	neat	300	200	benign
LP10	D	neat	500	350	benign
LP11	D	neat	500	350	benign
LP12	D	neat	500	350	benign
LP08	D	neat	300	200	benign
LP09	D	neat	300	200	benign
LP13	E	neat	300	200	benign
LP14	E	neat	300	200	benign
LP06	C	3.1	300	175	benign
LP07	C	3.1	300	175	benign
LP21	D	3.1	500	330	benign
LP22	D	3.1	500	330	benign
LP23	D	3.1	500	330	benign
LP15	D	3.1	300	175	explosion
LP16	D	3.1	300	175	benign
LP17	D	3.1	300	175	explosion
LP18	D	3.1	300	175	explosion
LP24	E	3.1	500	330	benign
LP25	E	3.1	500	330	benign
LP20	E	3.1	300	175	explosion
LP26	E	3.1	300	175	explosion
LP27	E	3.1	300	175	benign

TABLE 5. TABULATION OF PREVIOUS COMPRESSION IGNITION SENSITIVITY TESTS WITH RAPID-LOAD NOS-365 LIQUID MONOPROPELLANT CHARGE. ALL TESTS PERFORMED WITH $t_{DELAY} = 0$ (NO PRE-PRESSURIZATION)

RUN NO.	START-UP CURVE	PERCENT ULLAGE (VOLUME %)	INJECTION PRESSURE (psig)	SYSTEM RESPONSE
1	C	0	300	benign
2	E	0	300	explosion
3	C	3.1	300	benign
4	D	0	300	explosion
5	D	3.1	300	explosion
6	D	0	500	explosion
7	C	0	500	benign
8	C	3.1	150	explosion

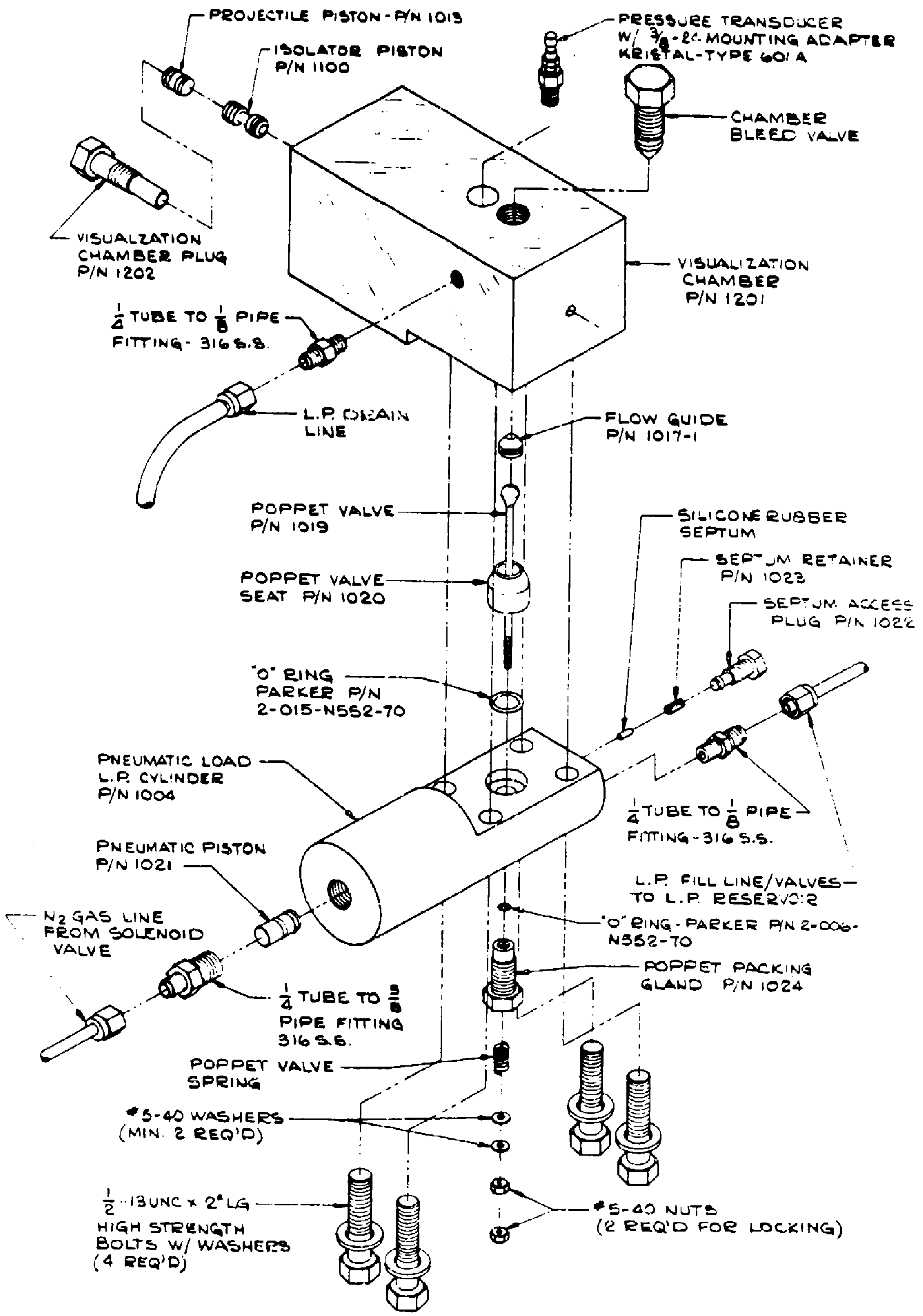


Figure 1. Assembly Drawing of Flow Visualization Tester.

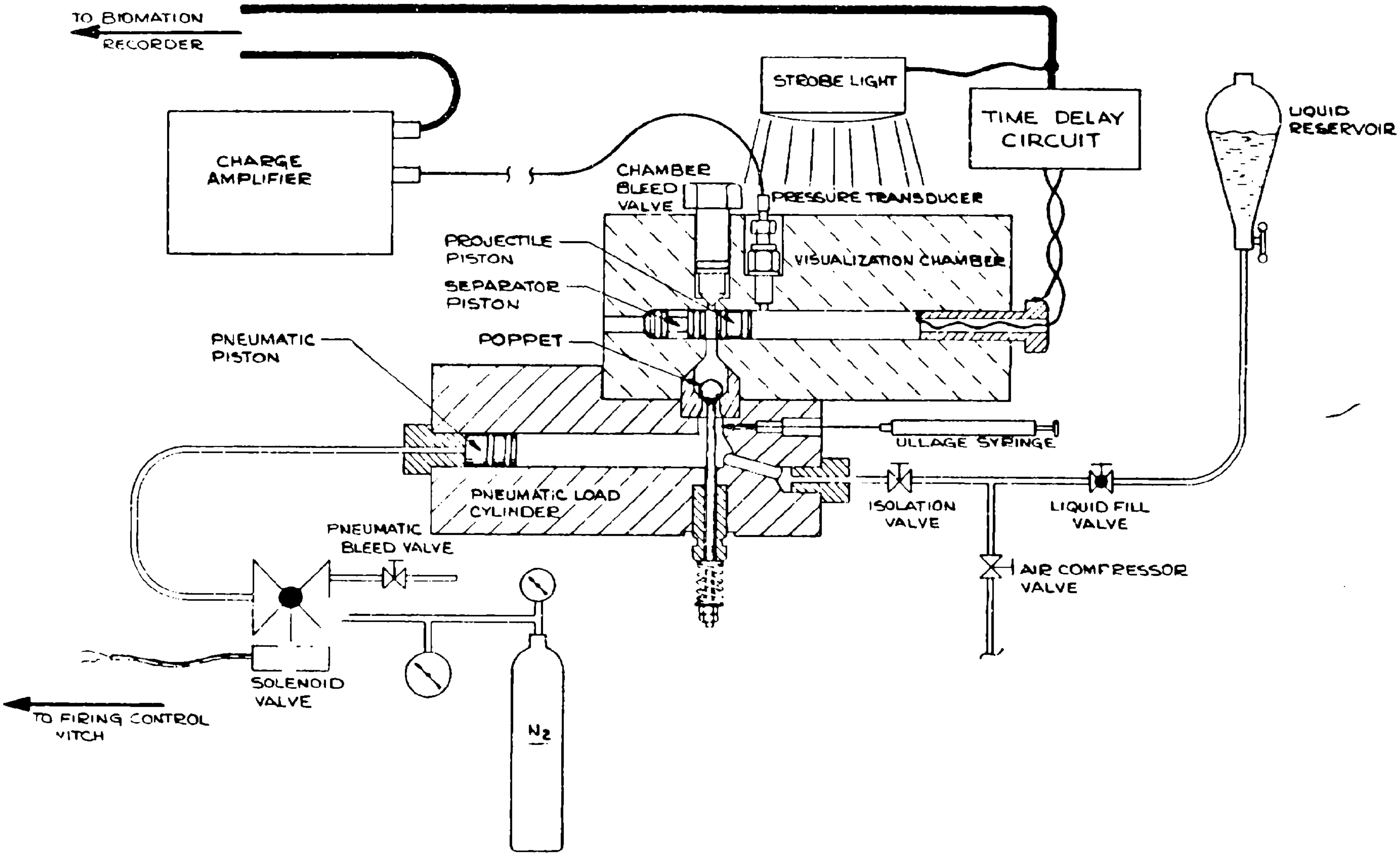


Figure 2. Functional Schematic Drawing of Flow Visualization Tester.

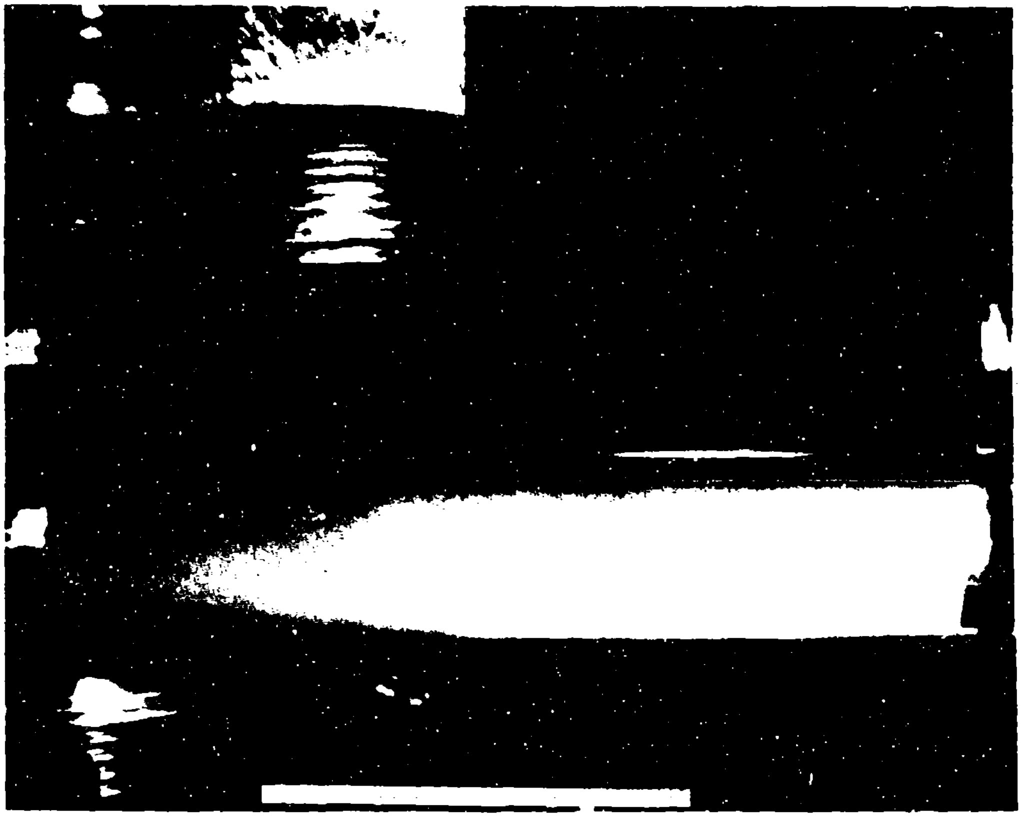
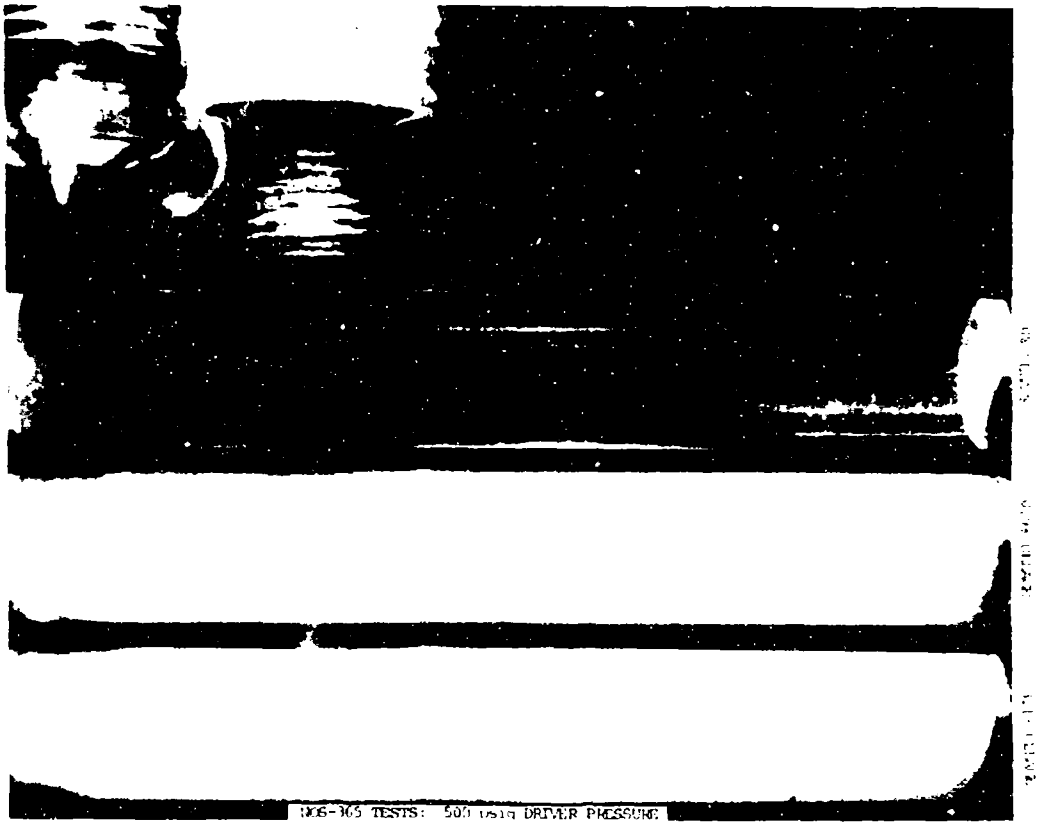


Figure 3. Photographs of Rapid-Load NOS-365 Liquid Monopropellant Charge at 500 psig Injection Pressure for Neat Propellant and 3.1% Volumetric Air Loading with t_{DELAY} = 10 msec.

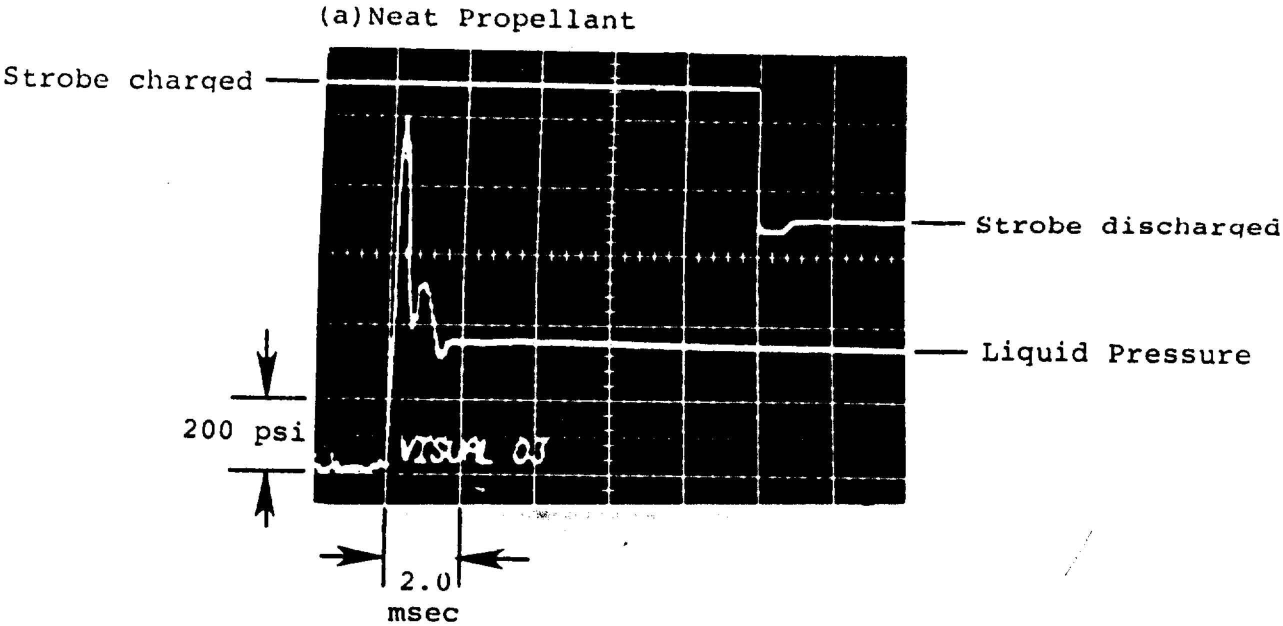


(a)

(b)

(c)

Figure 4. Photographs of Rapid-Load NOS-365 Liquid Monopropellant Charge at 500 psig Injection Pressure for Neat Propellant, 0.9%, and 3.1% Volumetric Air Loading with Zero Time Delay for System Fire.



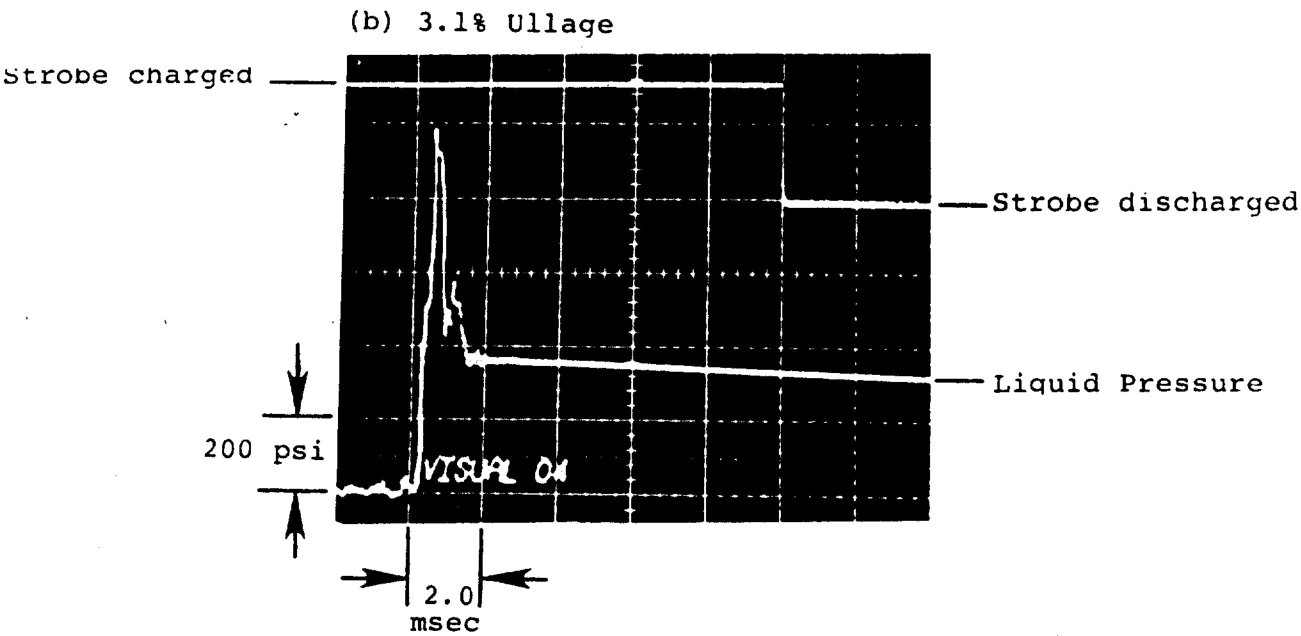
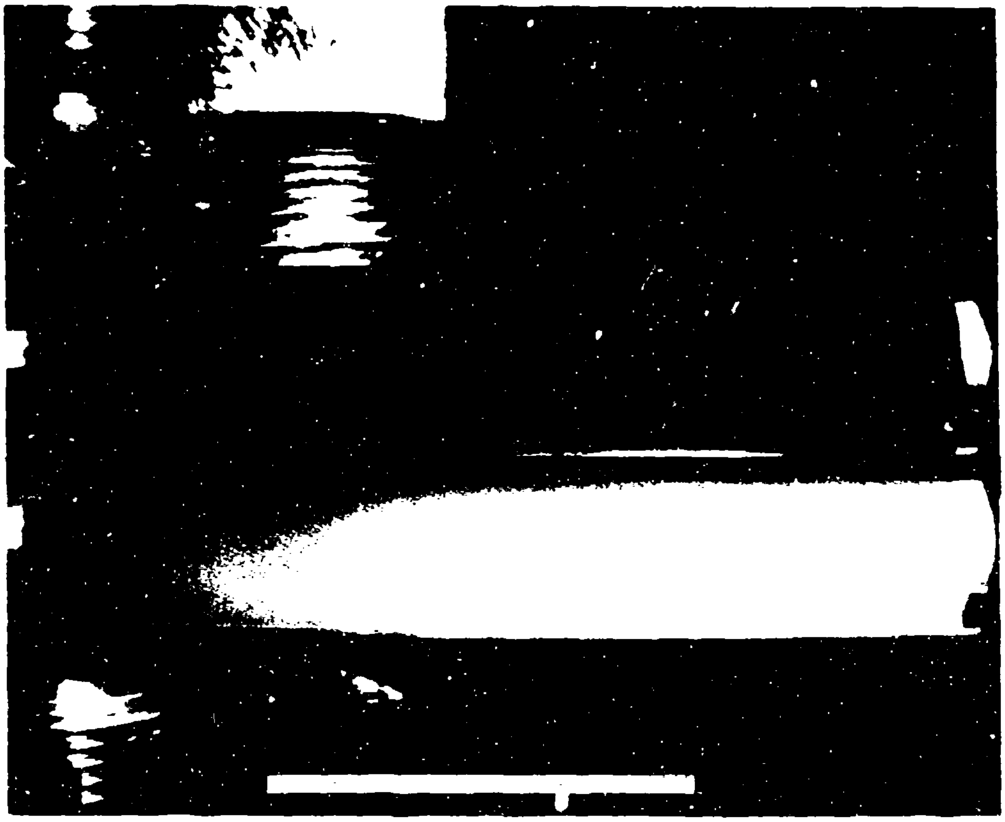


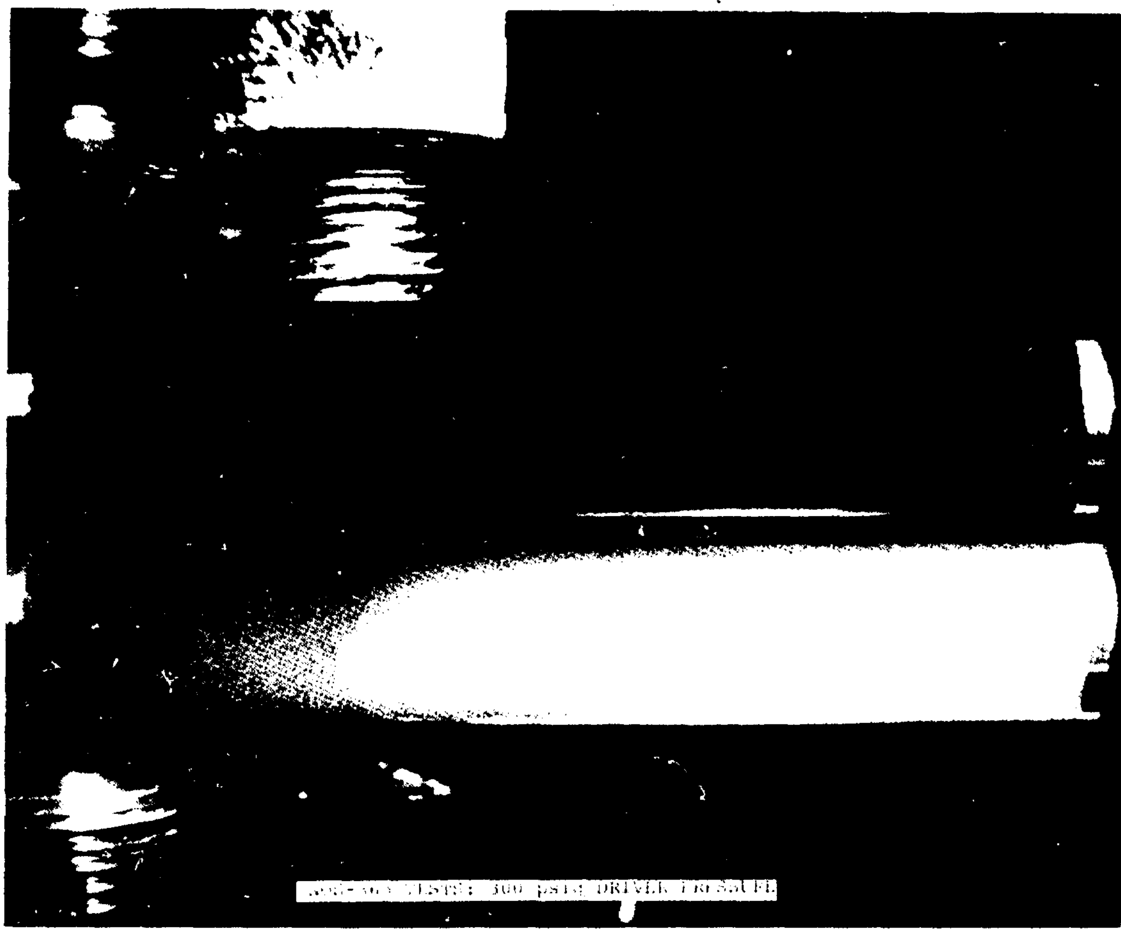
Figure 5. Oscilloscope Records of Rapid-Load Flow Visualization Tests with NOS-365 Liquid Monopropellant; Injection Pressure = 500 psig.



(a)

(b)

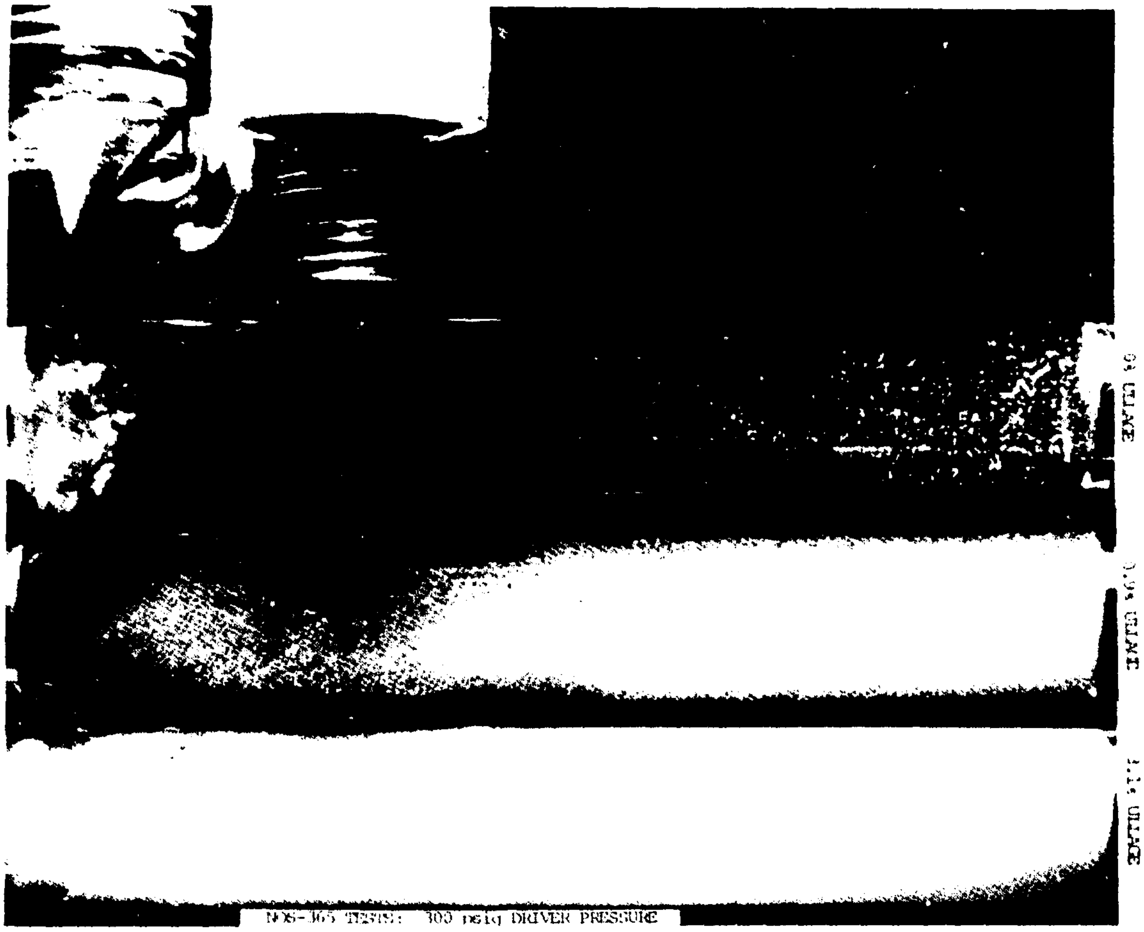
Figure 6. Photographs of Rapid-Load NOS-365 Liquid Monopropellant Charge at 300 psig Injection Pressure for Neat Propellant and 3.1% Volumetric Air Loading with t_{DELAY} = 10 msec.



(a)

(b)

Figure 6. Photographs of Rapid-Load NOS-365 Liquid Monopropellant Charge at 300 psig Injection Pressure for Neat Propellant and 3.1% Volumetric Air Loading with t_{DELAY} = 10 msec.



(a)

(b)

(c)

Figure 7. Photographs of Rapid-Load NOS-365 Liquid Monopropellant Charge at 300 psig Injection Pressure for Neat Propellant, 0.9%, and 3.1% Volumetric Air Loading with Zero Time Delay for System Fire.

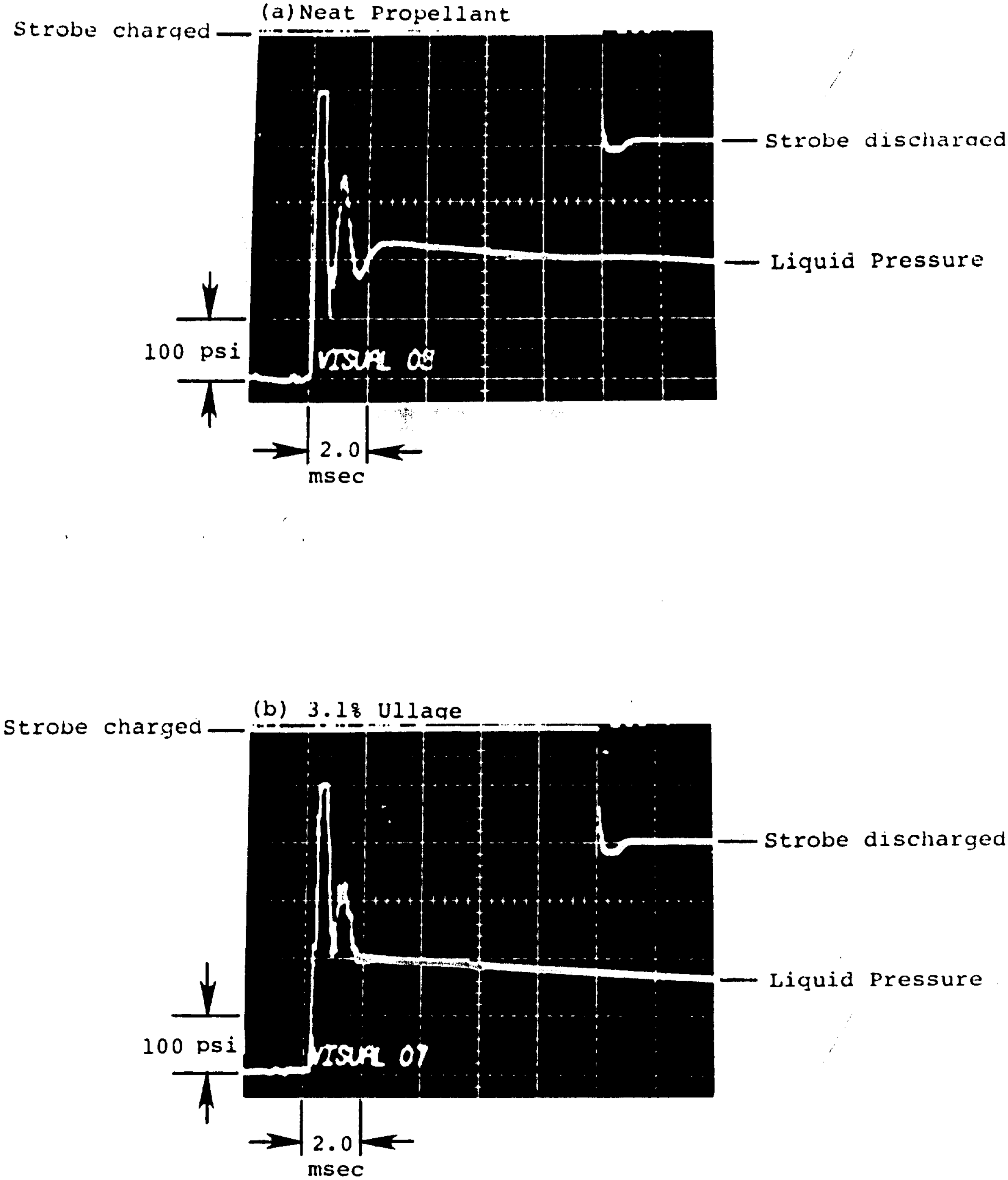


Figure 8. Oscilloscope Records of Rapid-Load Flow Visualization Tests with NOS-365 Liquid Monopropellant; Injection Pressure = 300 psig.

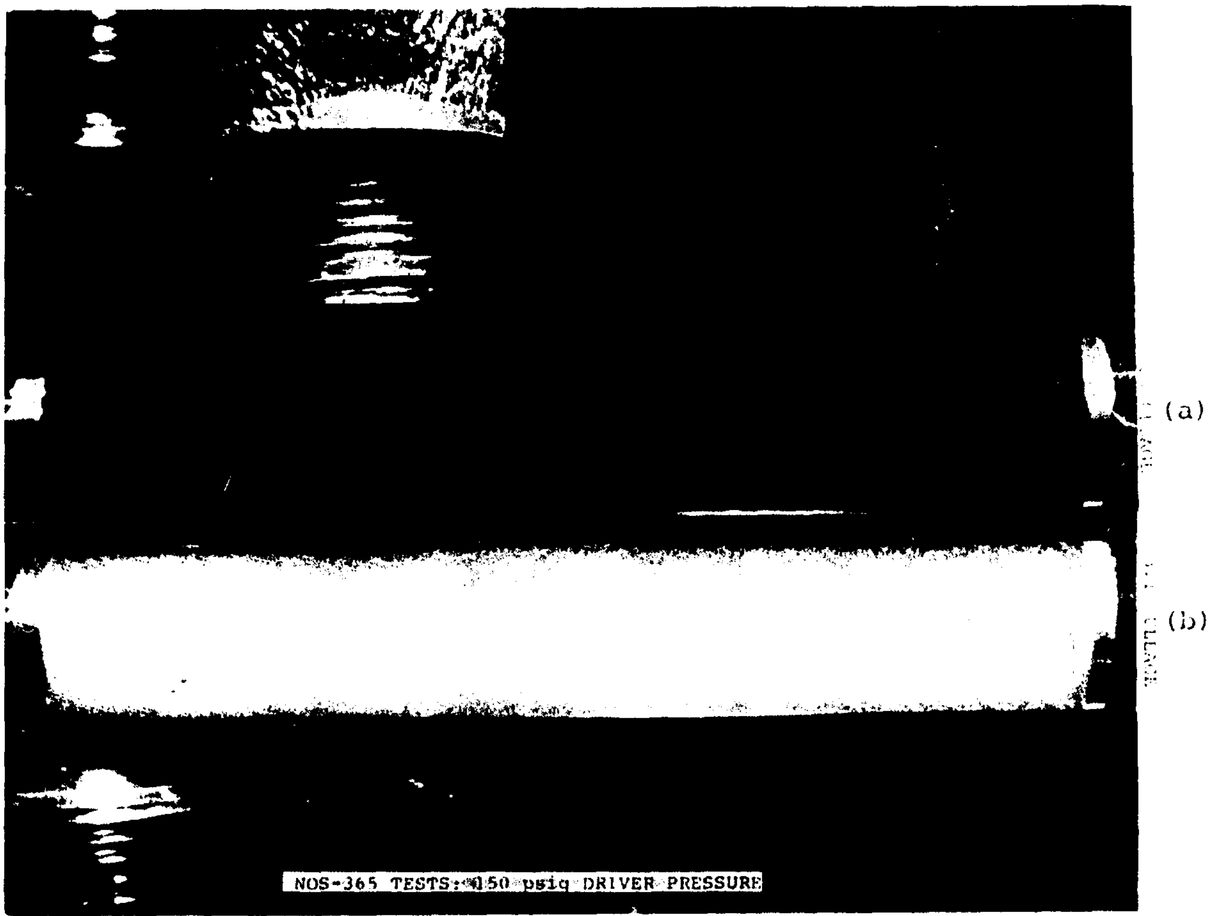
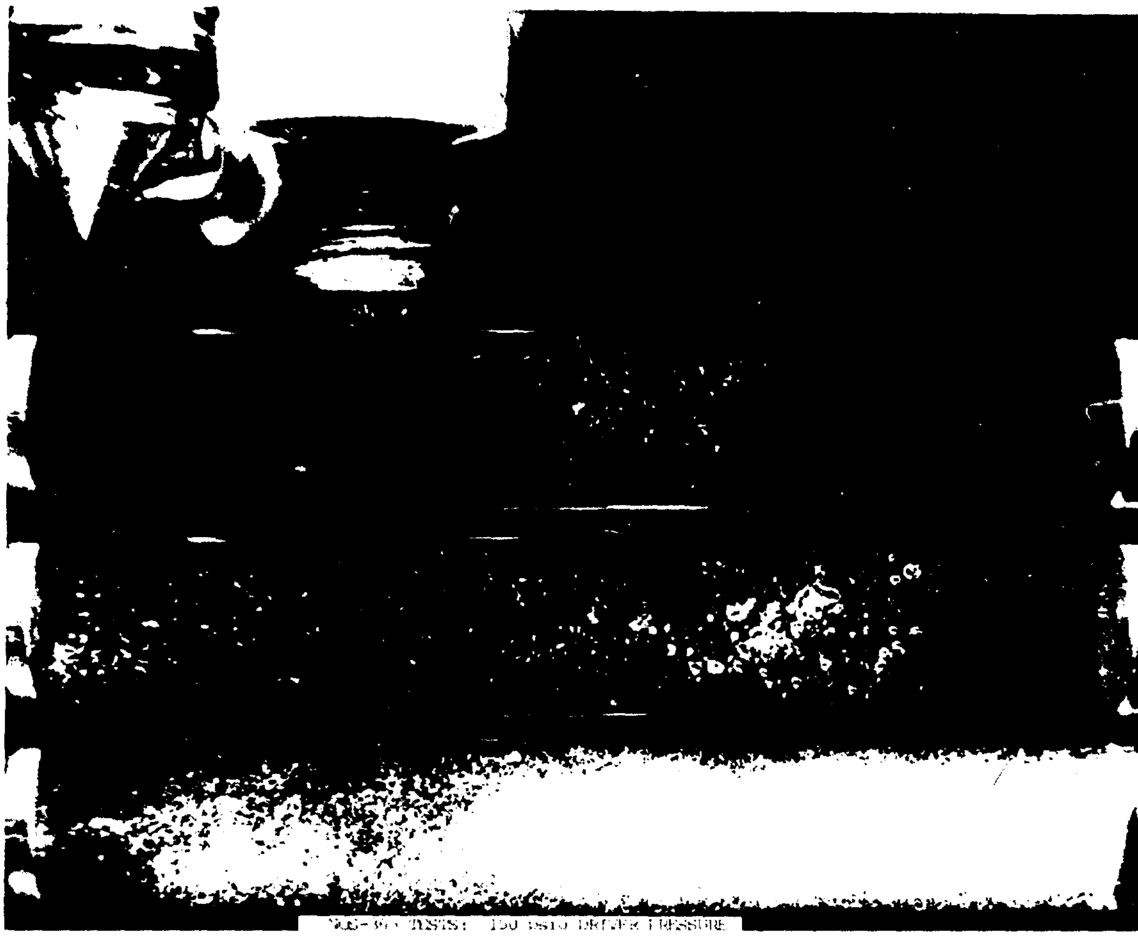


Figure 9. Photographs of Rapid-Load NOS-365 Liquid Monopropellant Charge at 150 psig Injection Pressure for Neat Propellant and 3.1% Volumetric Air Loading with t_{DELAY} = 10 msec.



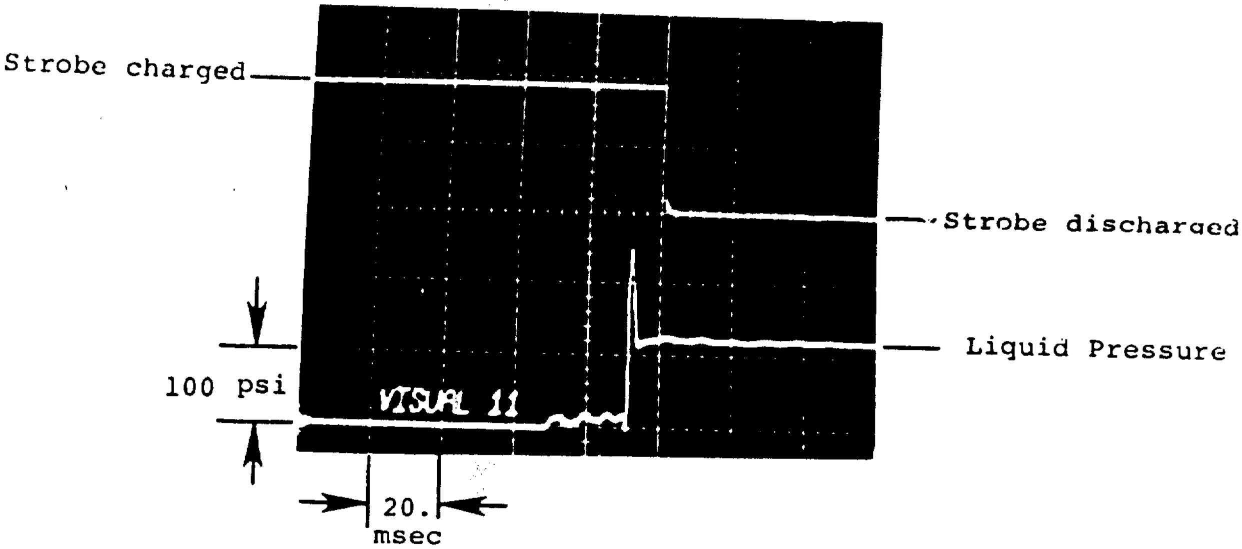
(a)

(b)

(c)

Figure 10. Photographs of Rapid-Load NOS-365 Liquid Monopropellant Charge at 150 psig Injection Pressure for Neat Propellant, 0.9%, and 3.1% Volumetric Air Loading with Zero Time Delay for System Fire.

(a) Neat Propellant



(b) 3.1% Ullage

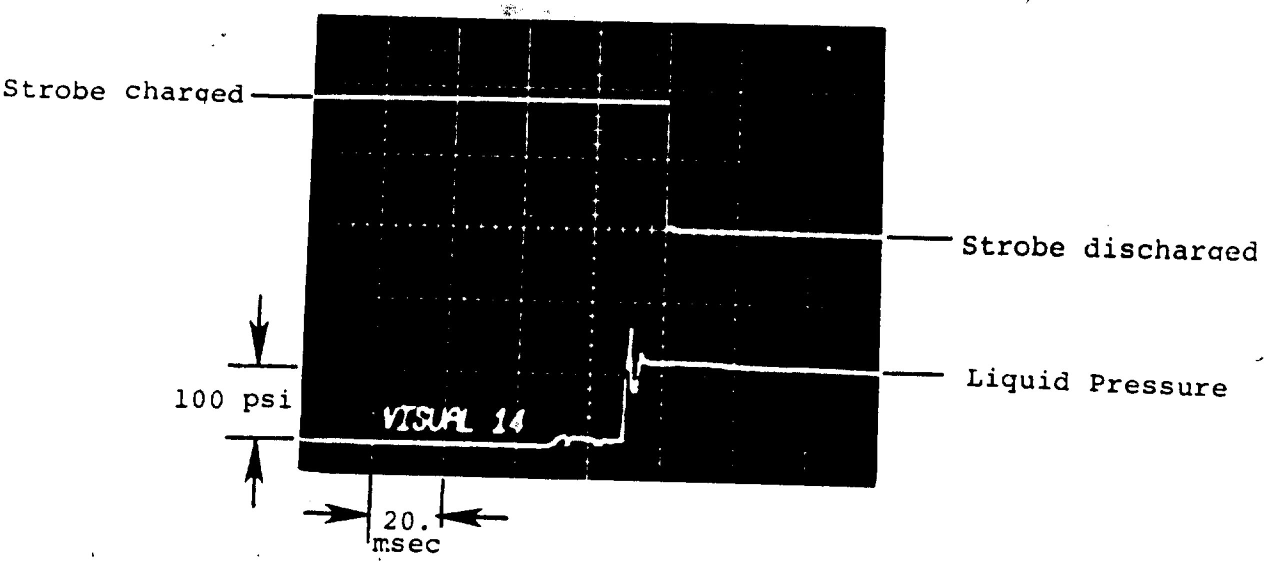


Figure 11. Oscilloscope Records of Rapid-Load Flow Visualization Tests with NOS-365 Liquid Monopropellant; Injection Pressure = 150 psig.

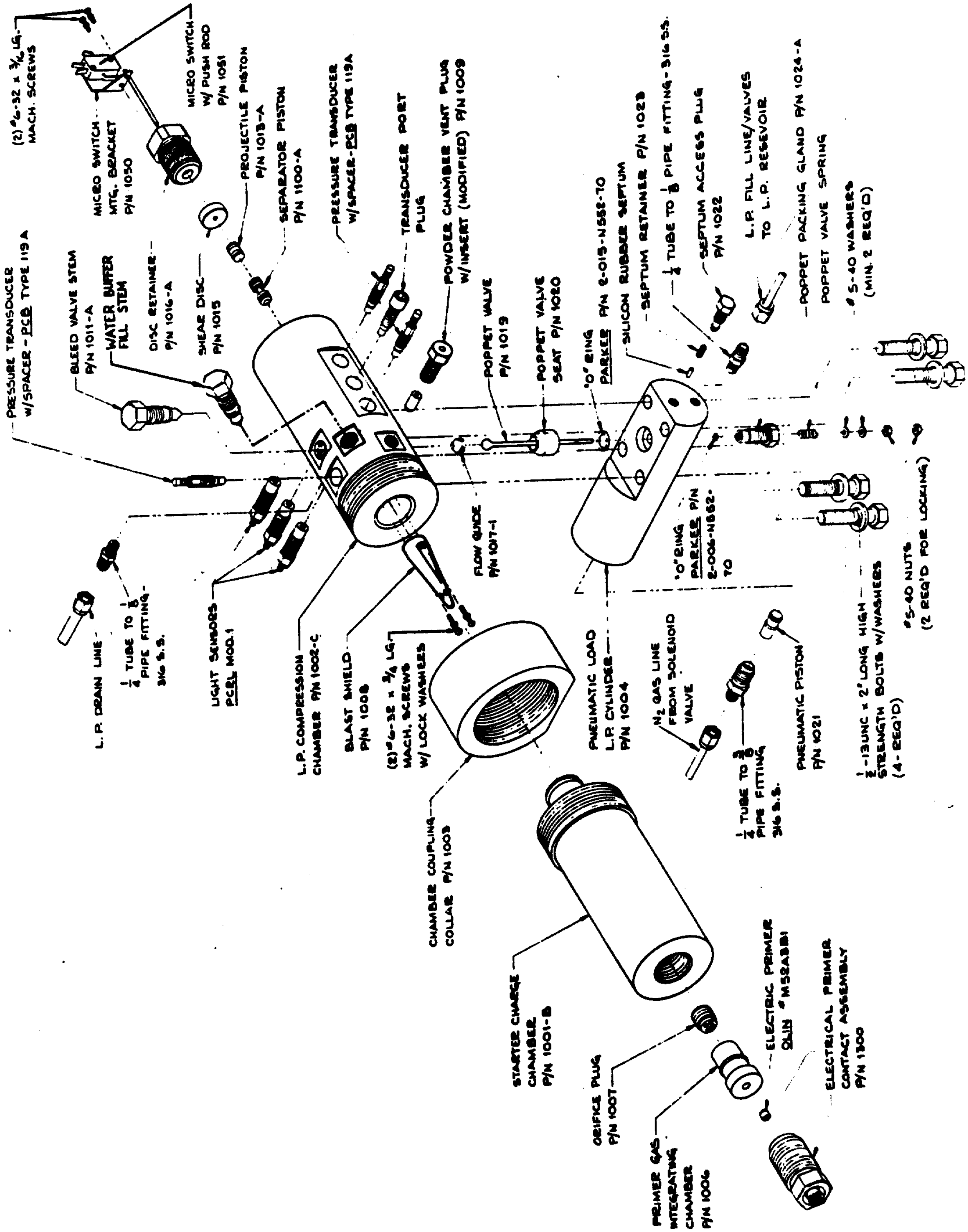


Figure 12. Assembly Drawing of Compression Ignition Sensitivity Tester.

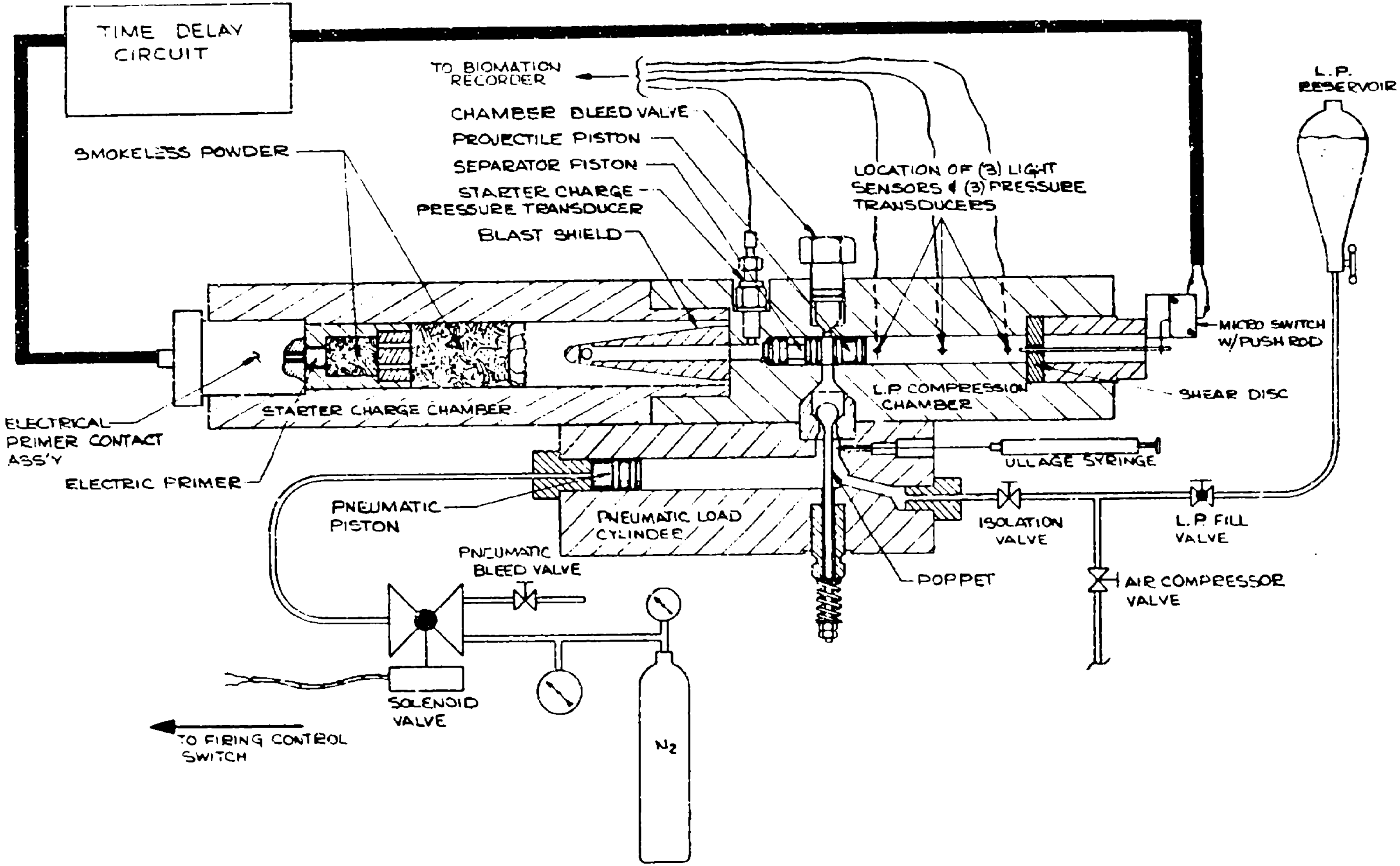


Figure 13. Functional Schematic Drawing of Compression Ignition Sensitivity Tester.

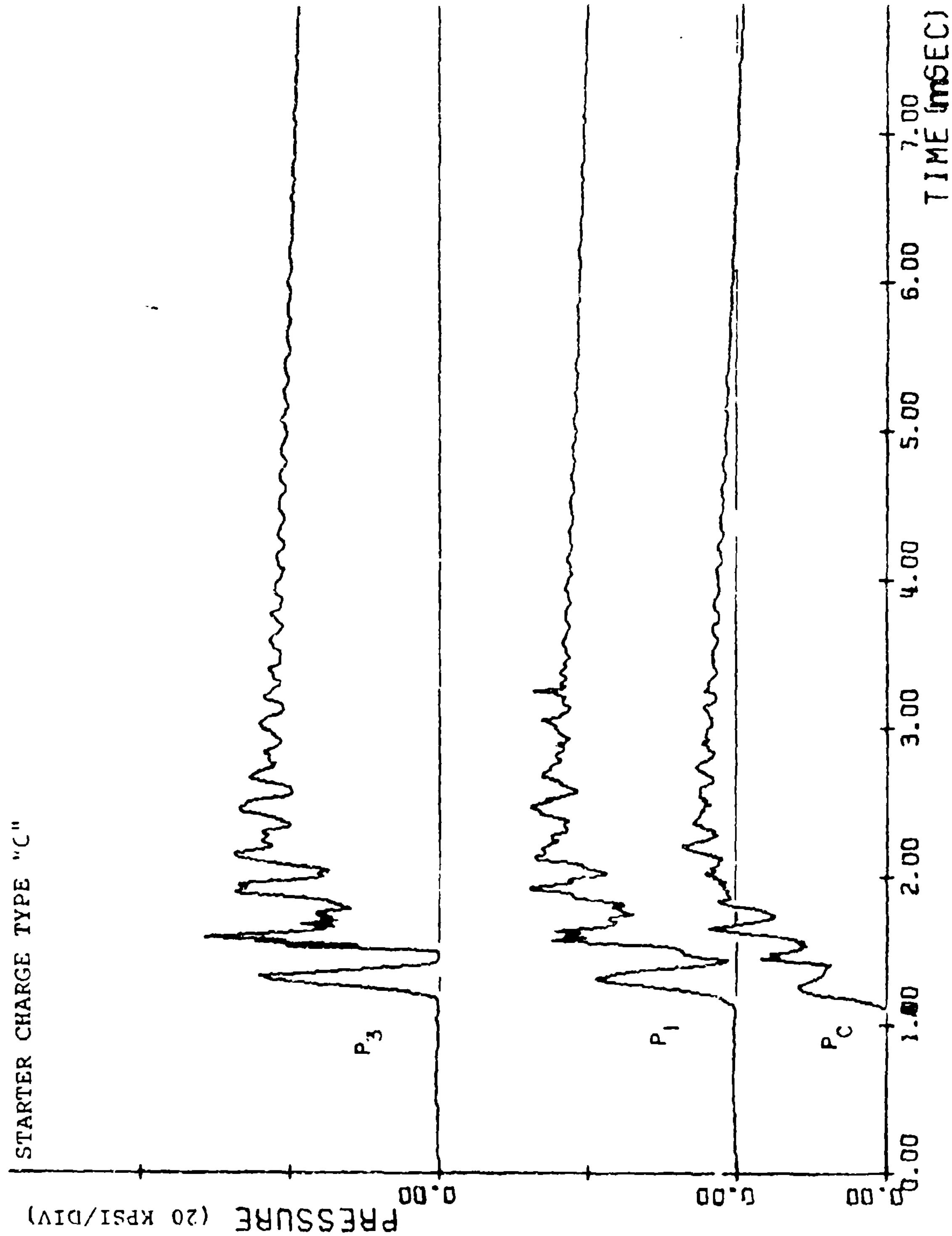


Figure 14a. Pressure-time Histories for Inert Simulant Tests with Oscillations in Starter Charge Pressurization: Al/Nylon Composite Separator Piston

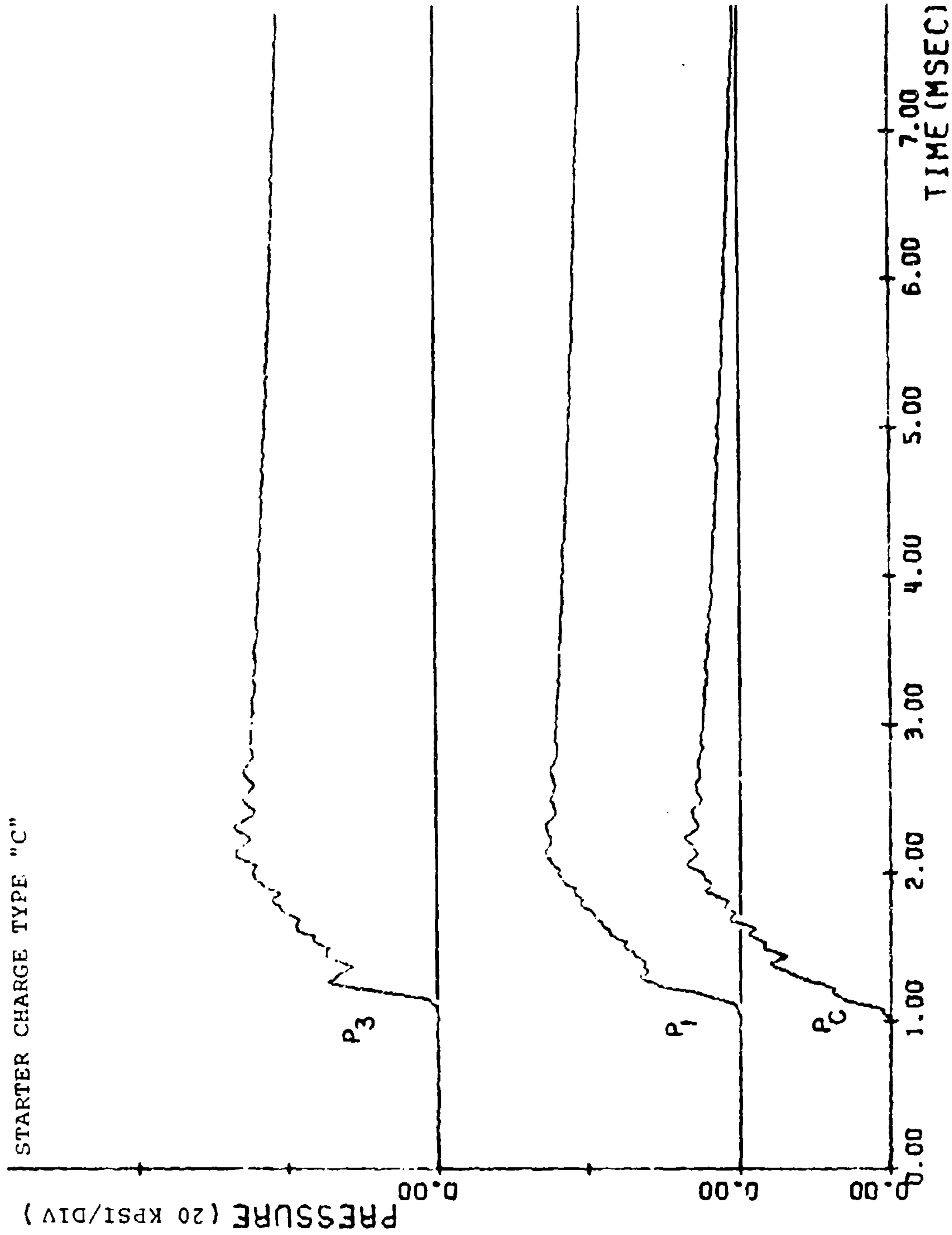


Figure 14b. Pressure-time Histories for Inert Simulant Tests:
Al with Water Annulus Separator Piston

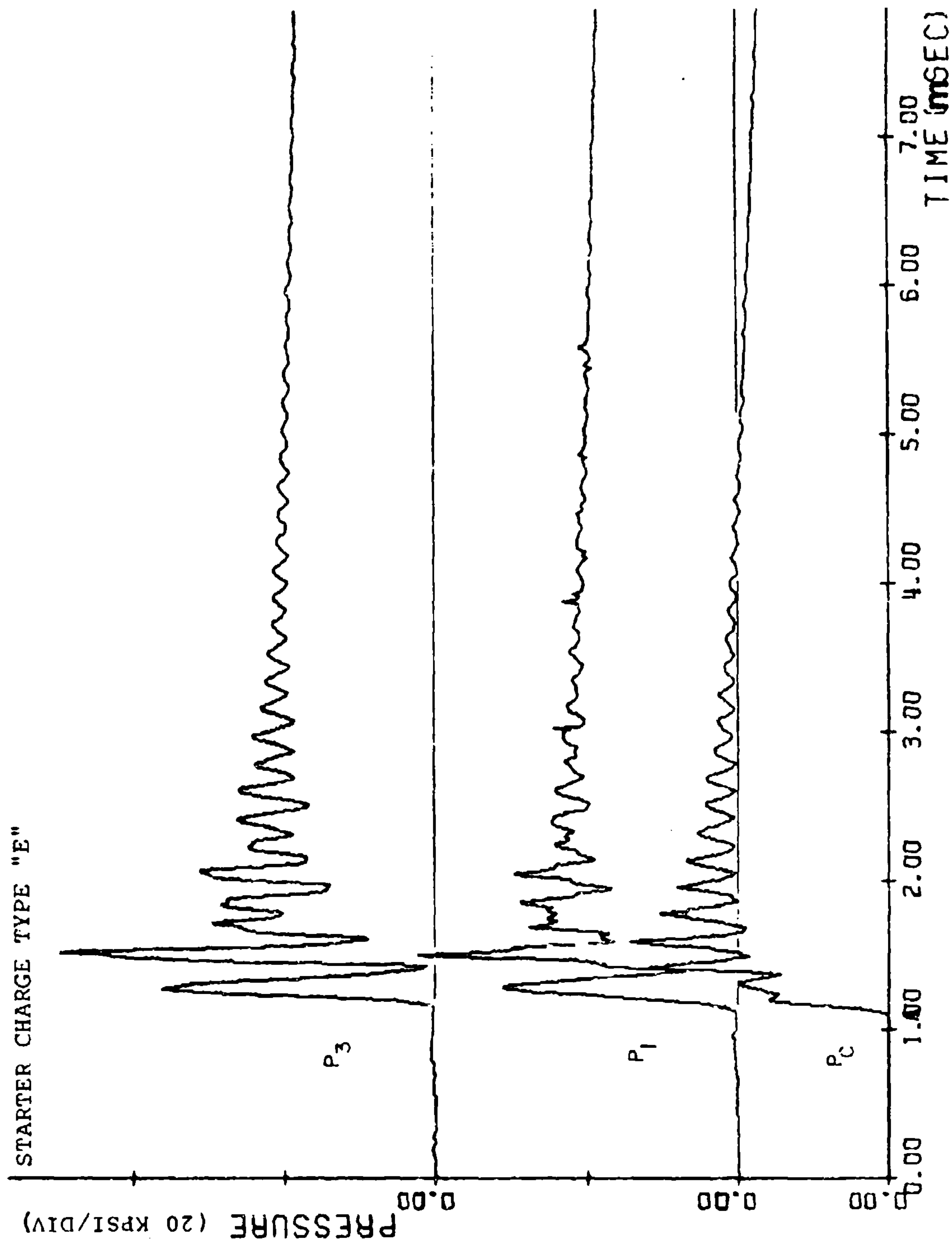


Figure 15a. Pressure-time Histories for Inert Simulant Tests with Oscillations in Starter Charge Pressurization: Al/Nylon Composite Separator Piston

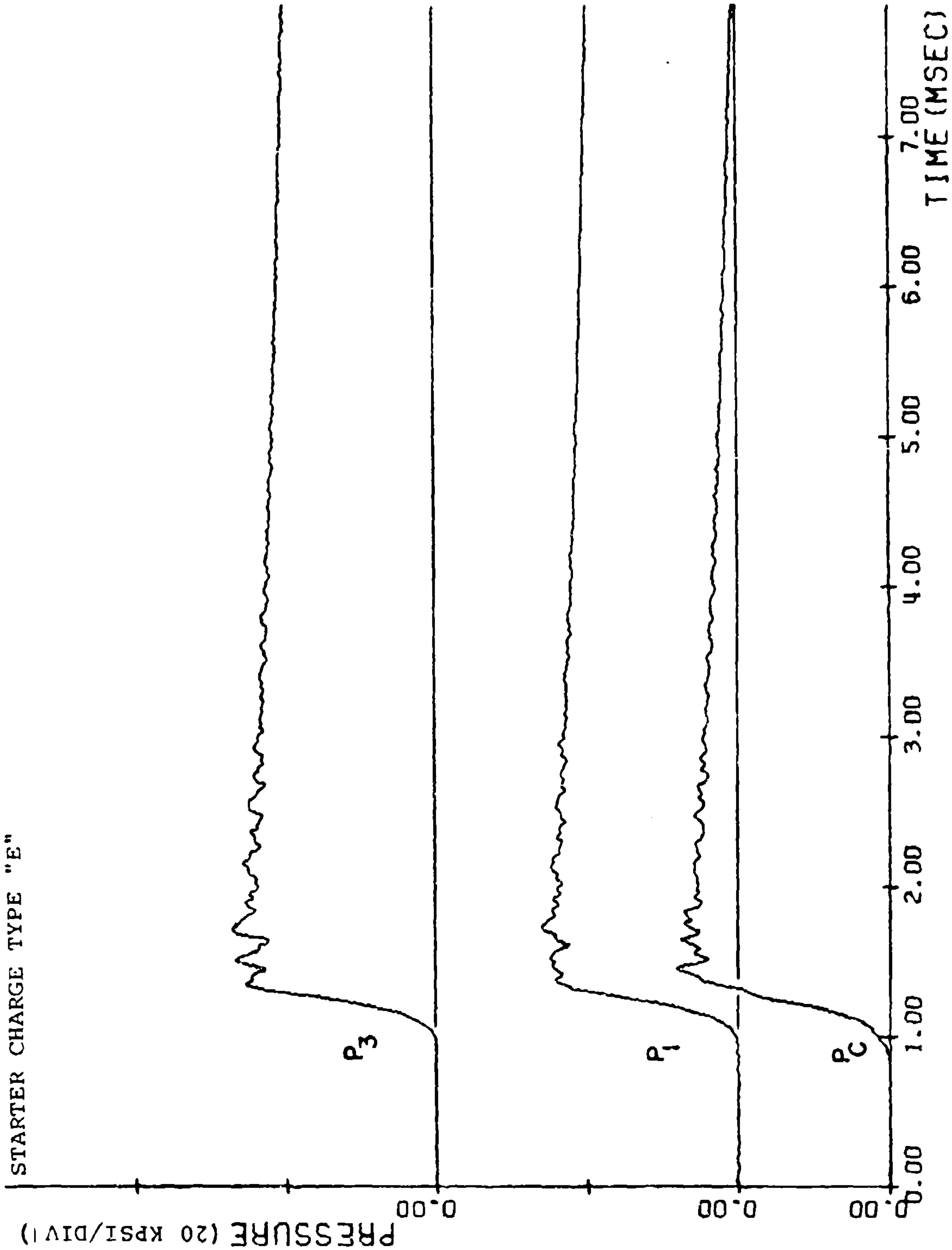


Figure 15b. Pressure-time Histories for Inert Simulant Tests: Al with Water Annulus Separator Piston

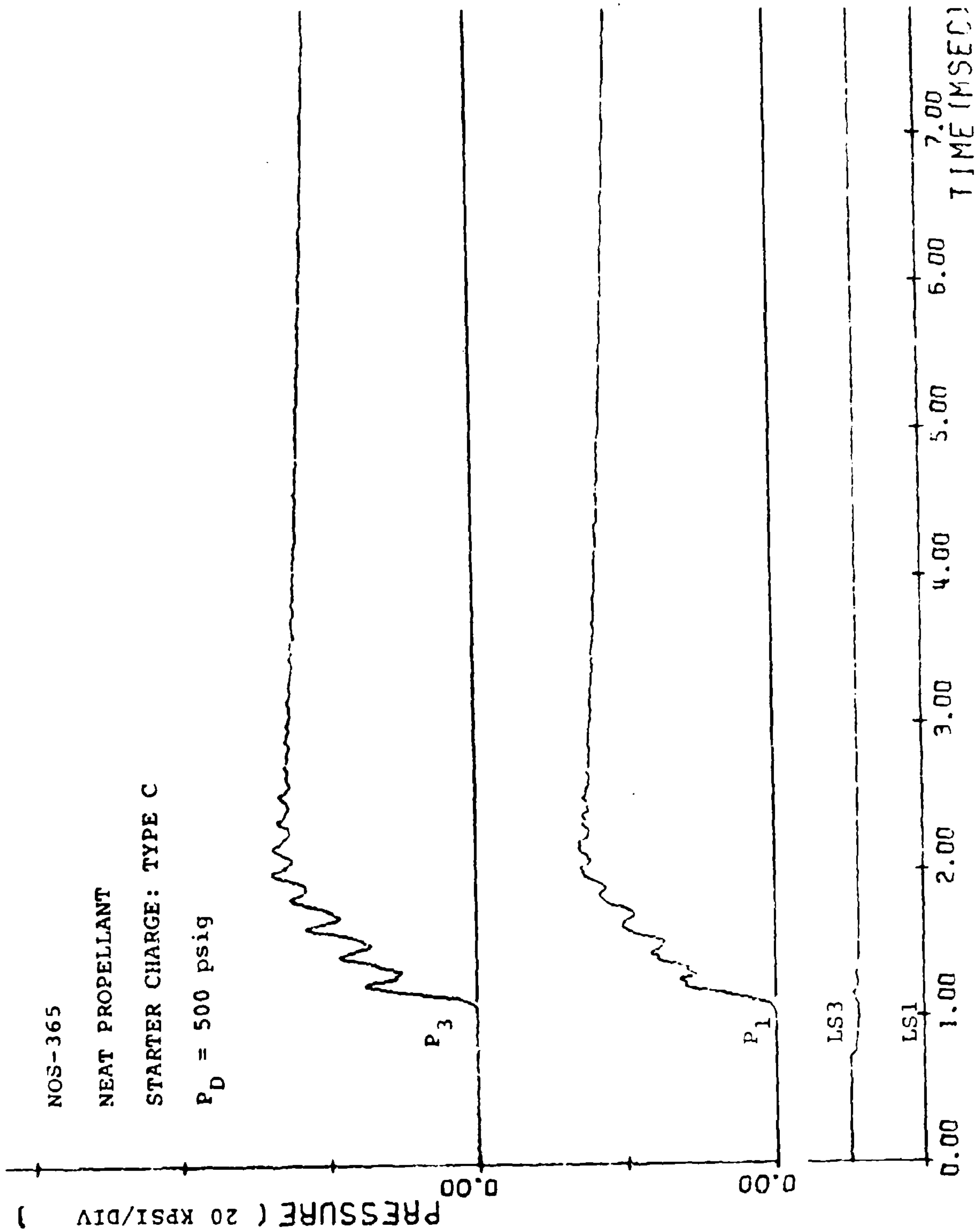


Figure 16. NOS-365 Starter Charge: Type C

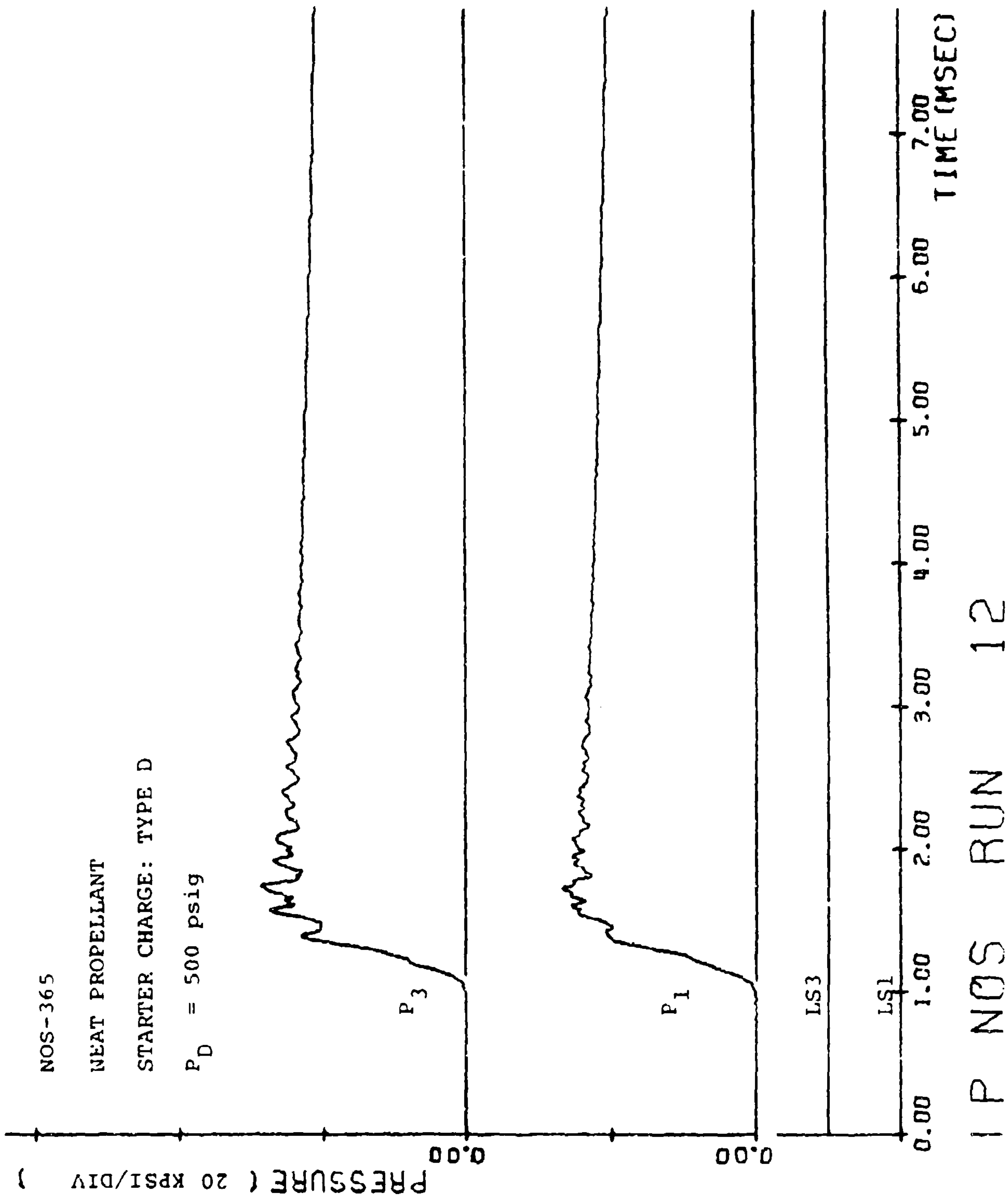


Figure 17. NOS-365 Starter Charge: Type D

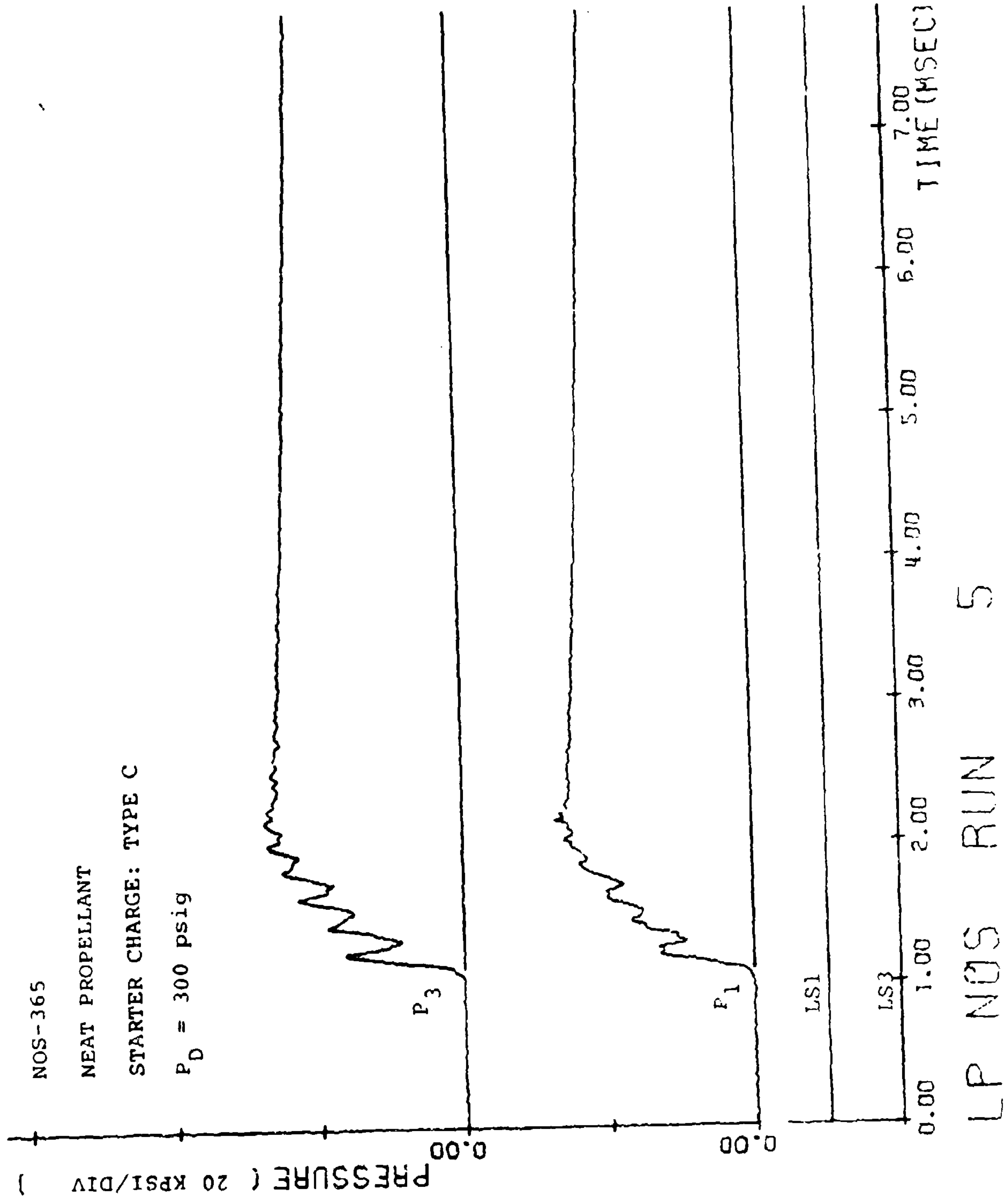


Figure 18. NOS-355 Starter Charge: Type C

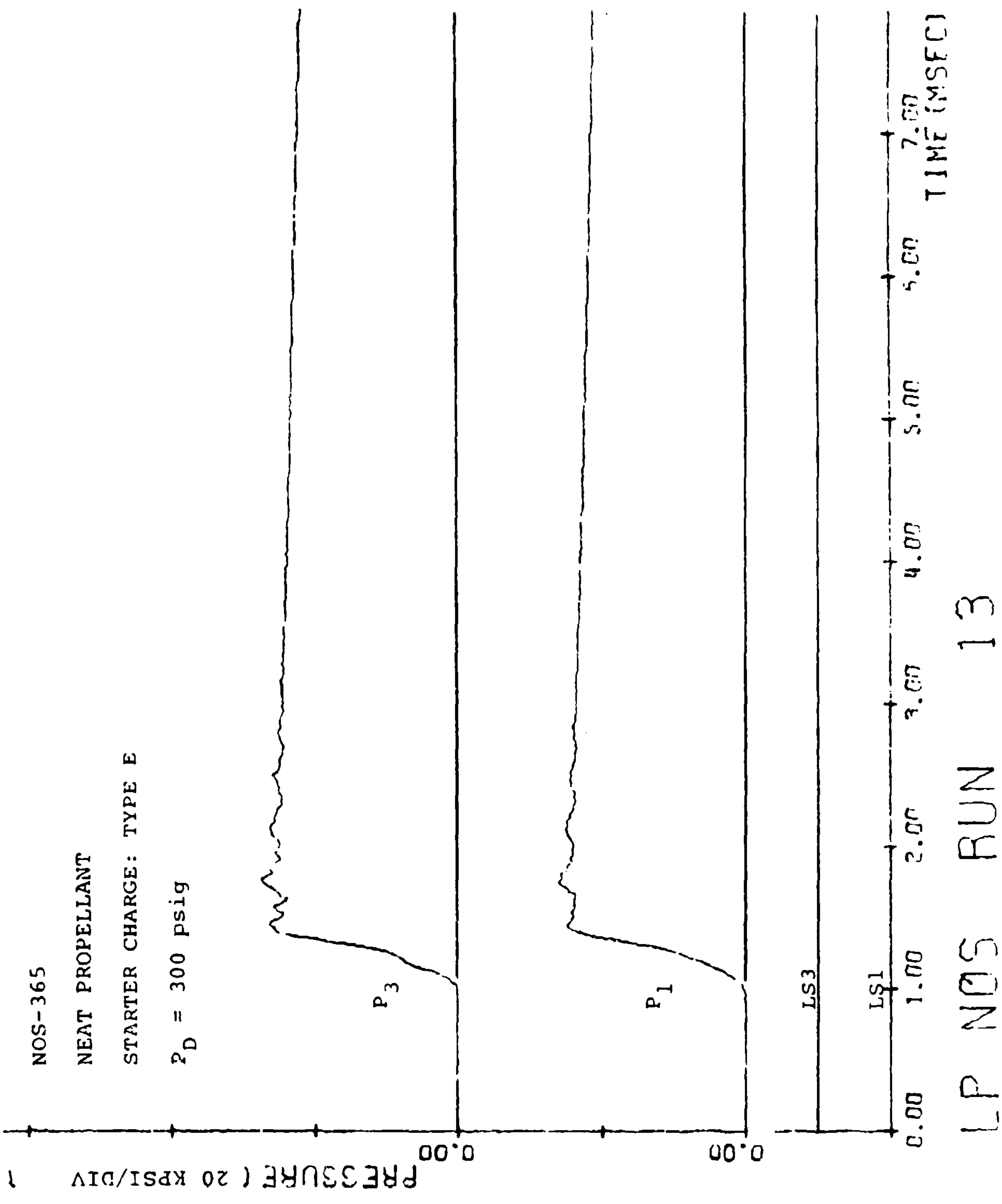


Figure 19. NOS-365 Starter Charge: Type E

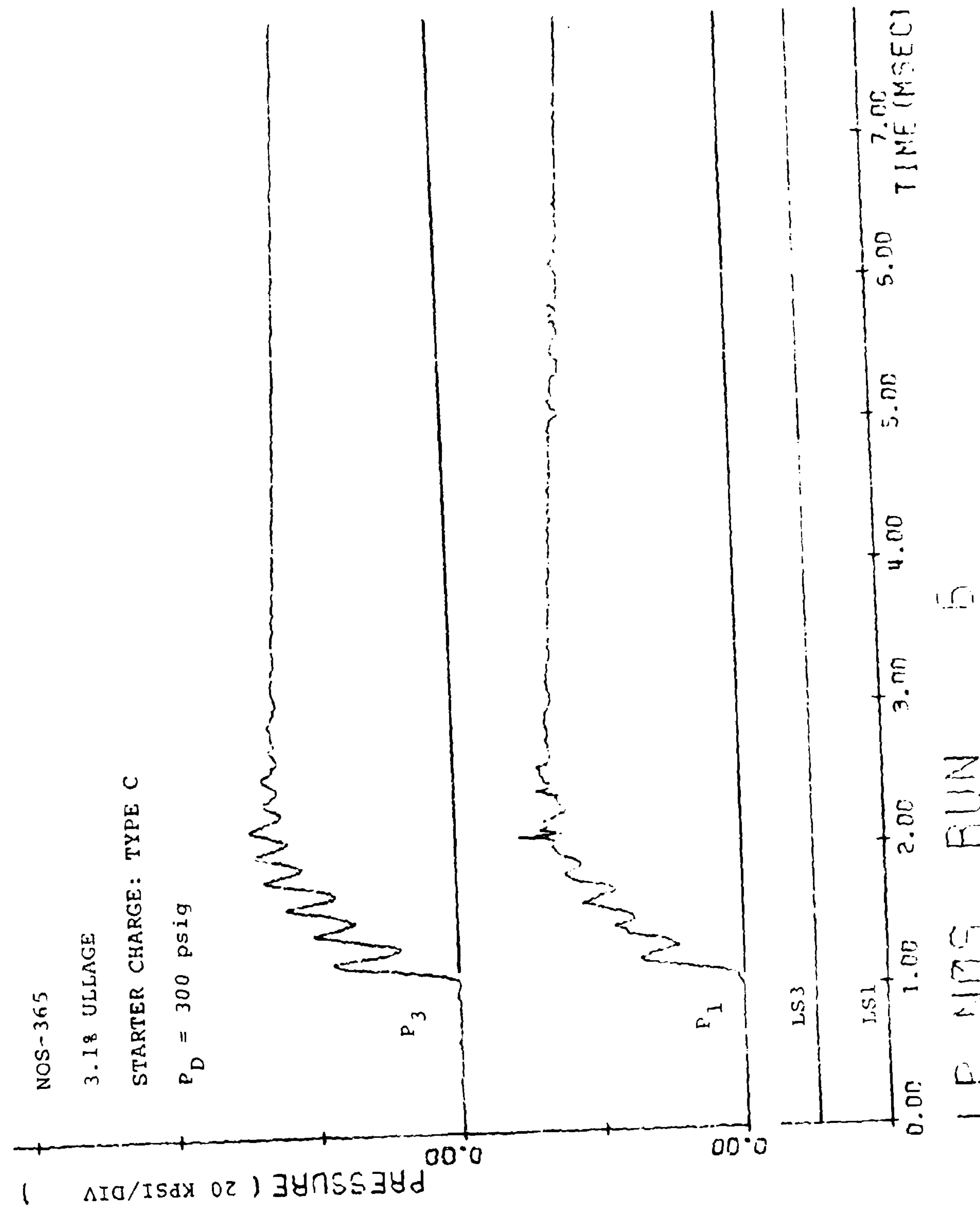


Figure 20. NOS-365 Starter Charge: Type C

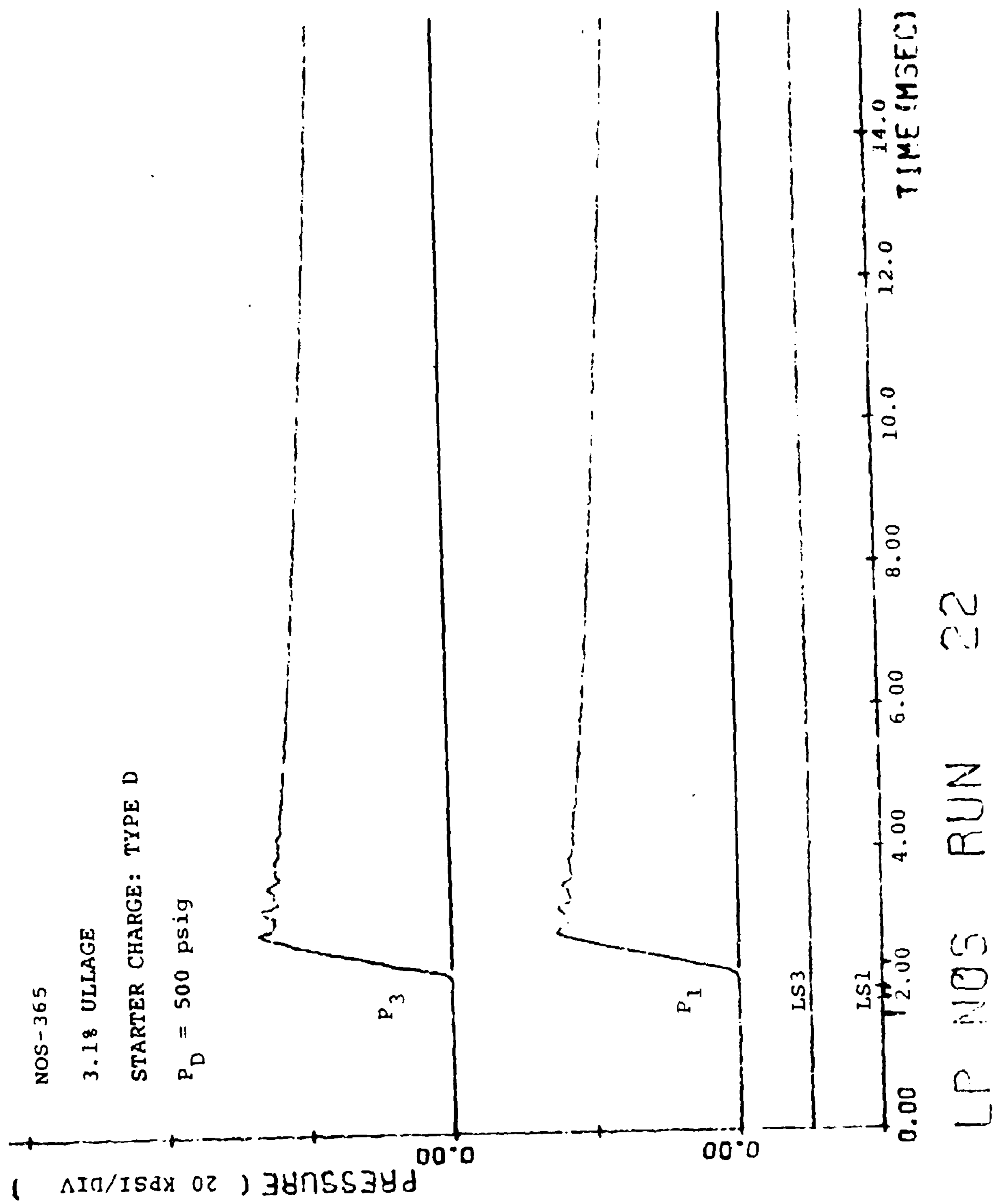


Figure 21. NOS-365 Starter Charge: Type D

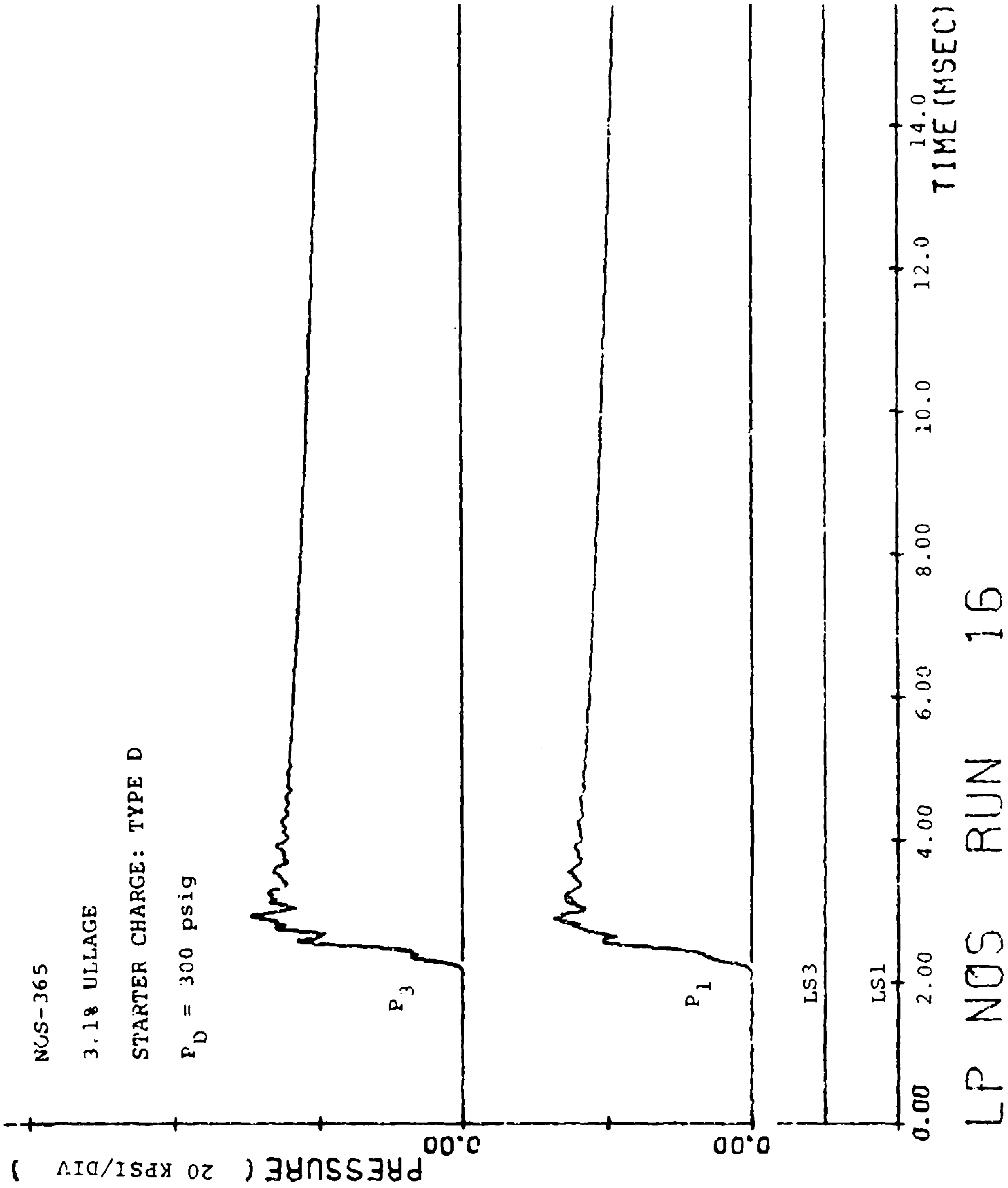


Figure 22. NOS-365 Starter Charge: Type D

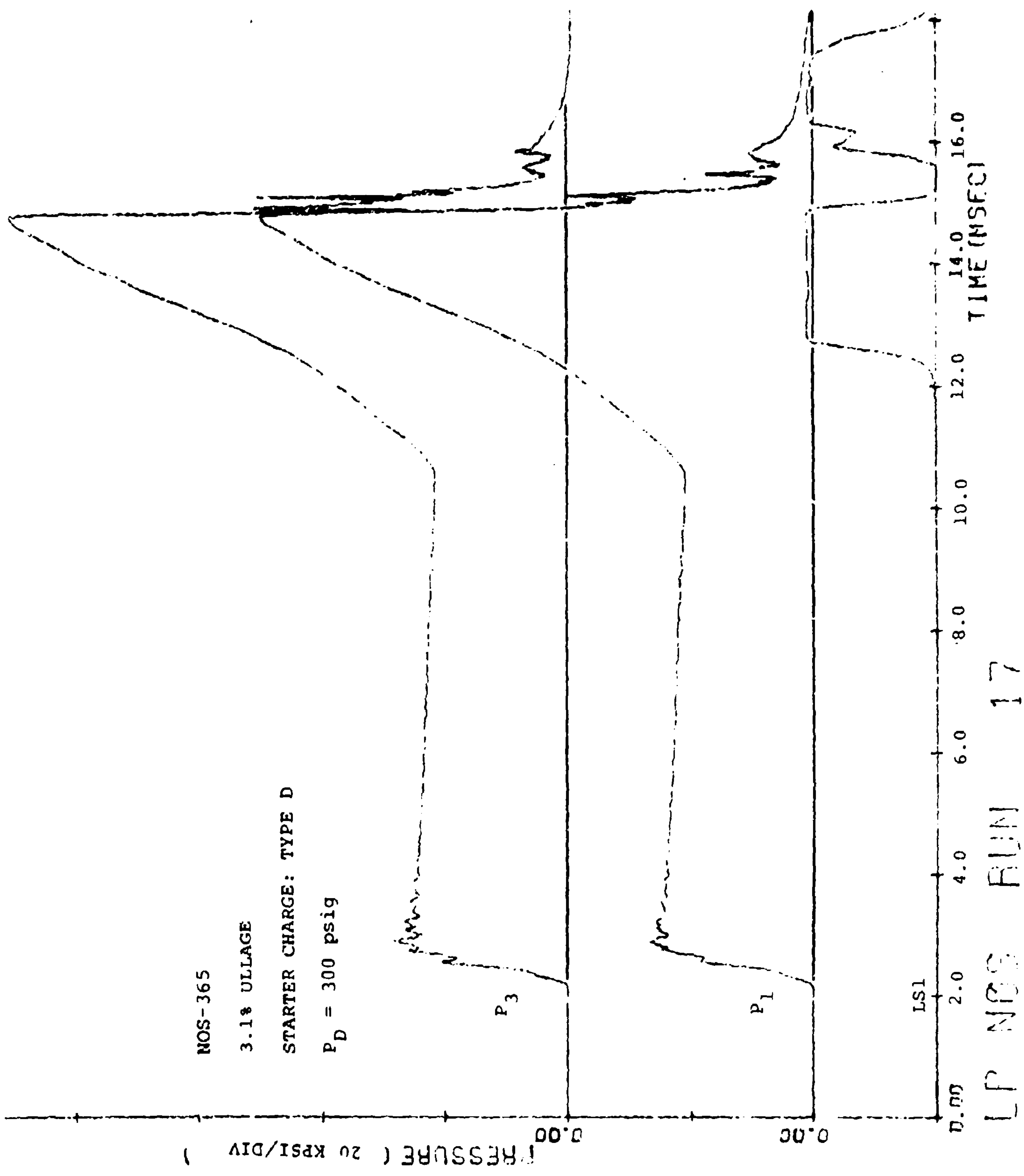


Figure 23. NOS-365 Starter Charge: Type D

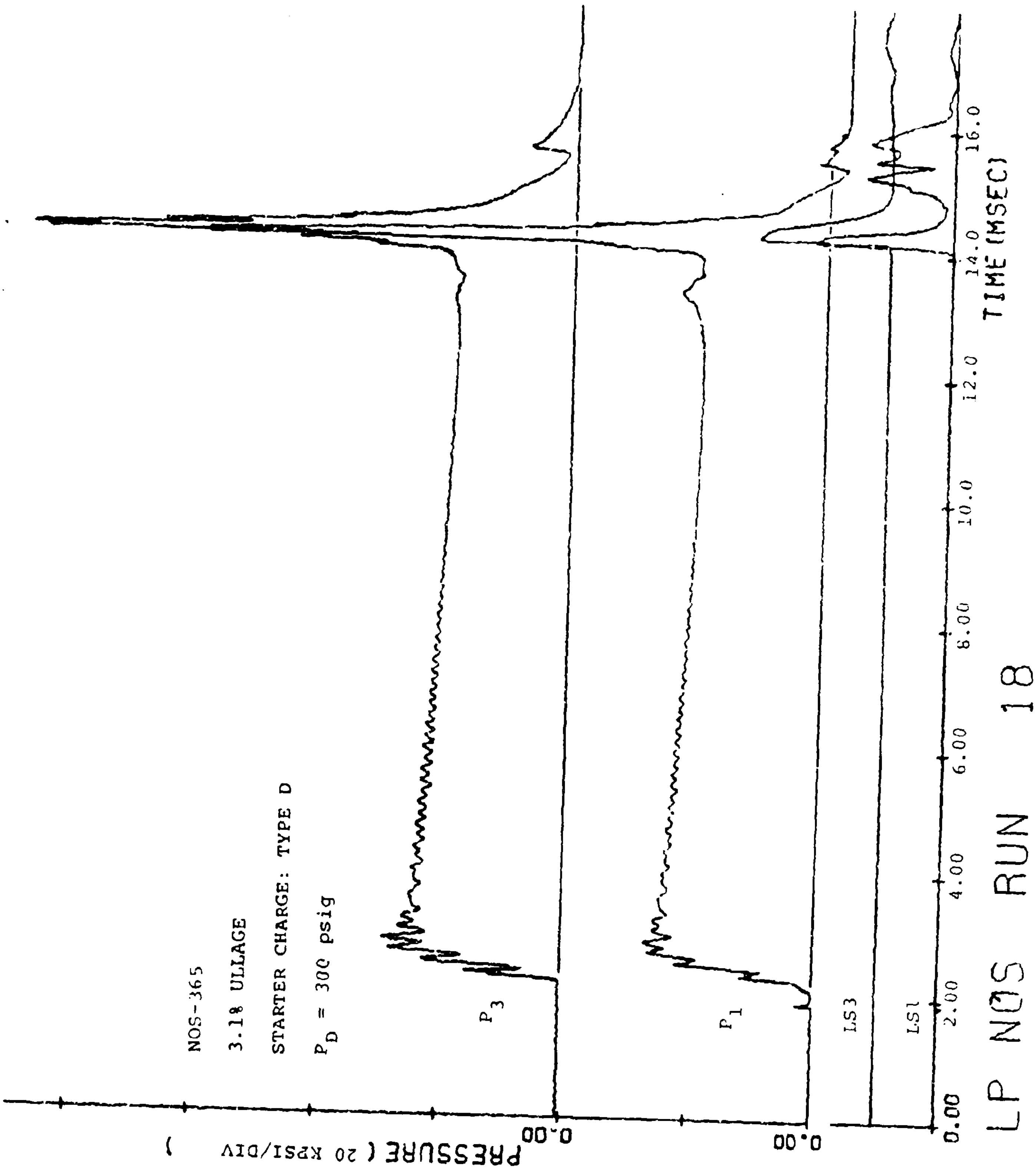


Figure 24. NOS-365 Starter Charge: Type D

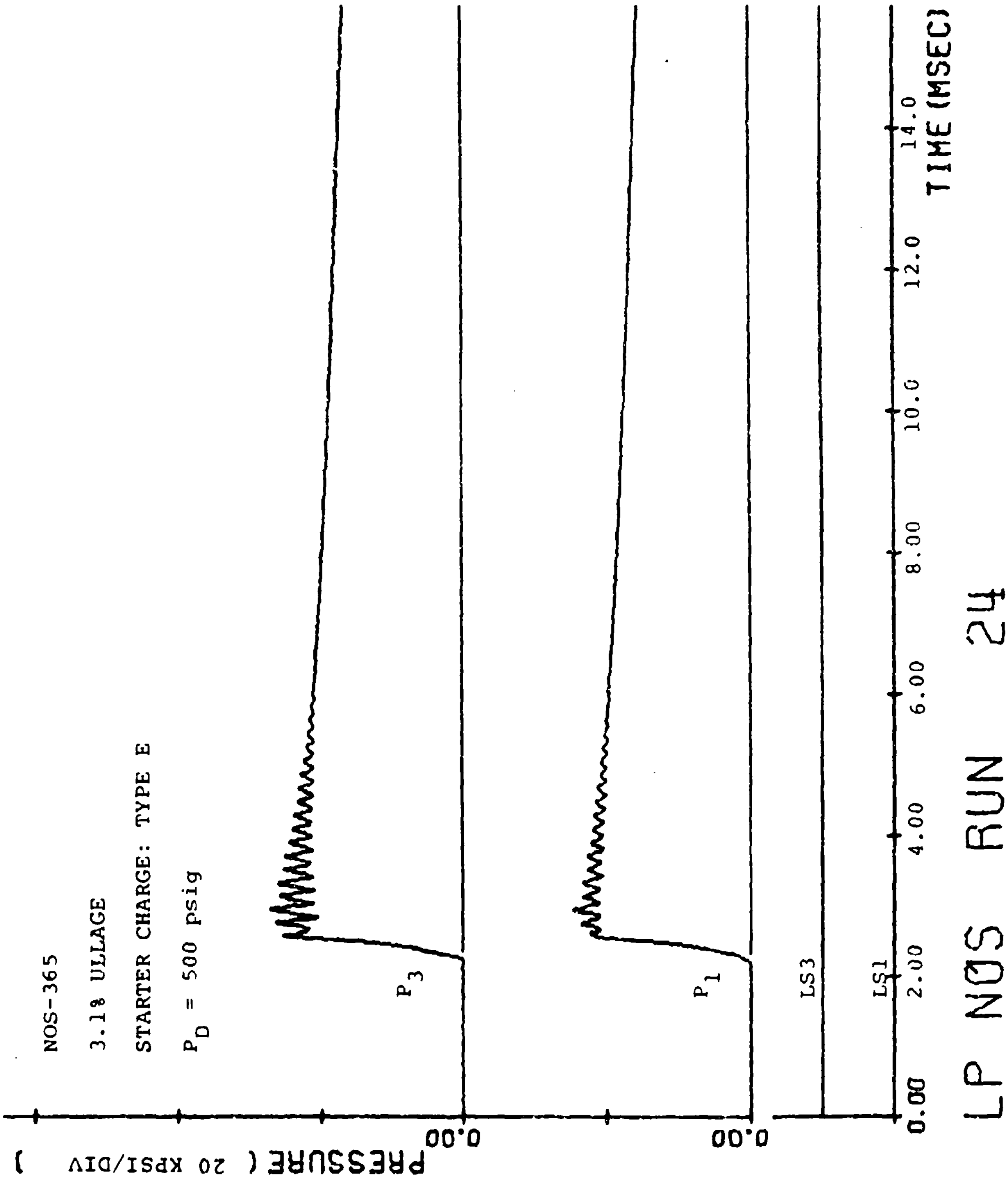


Figure 25. NOS-365 Starter Charge: Type E

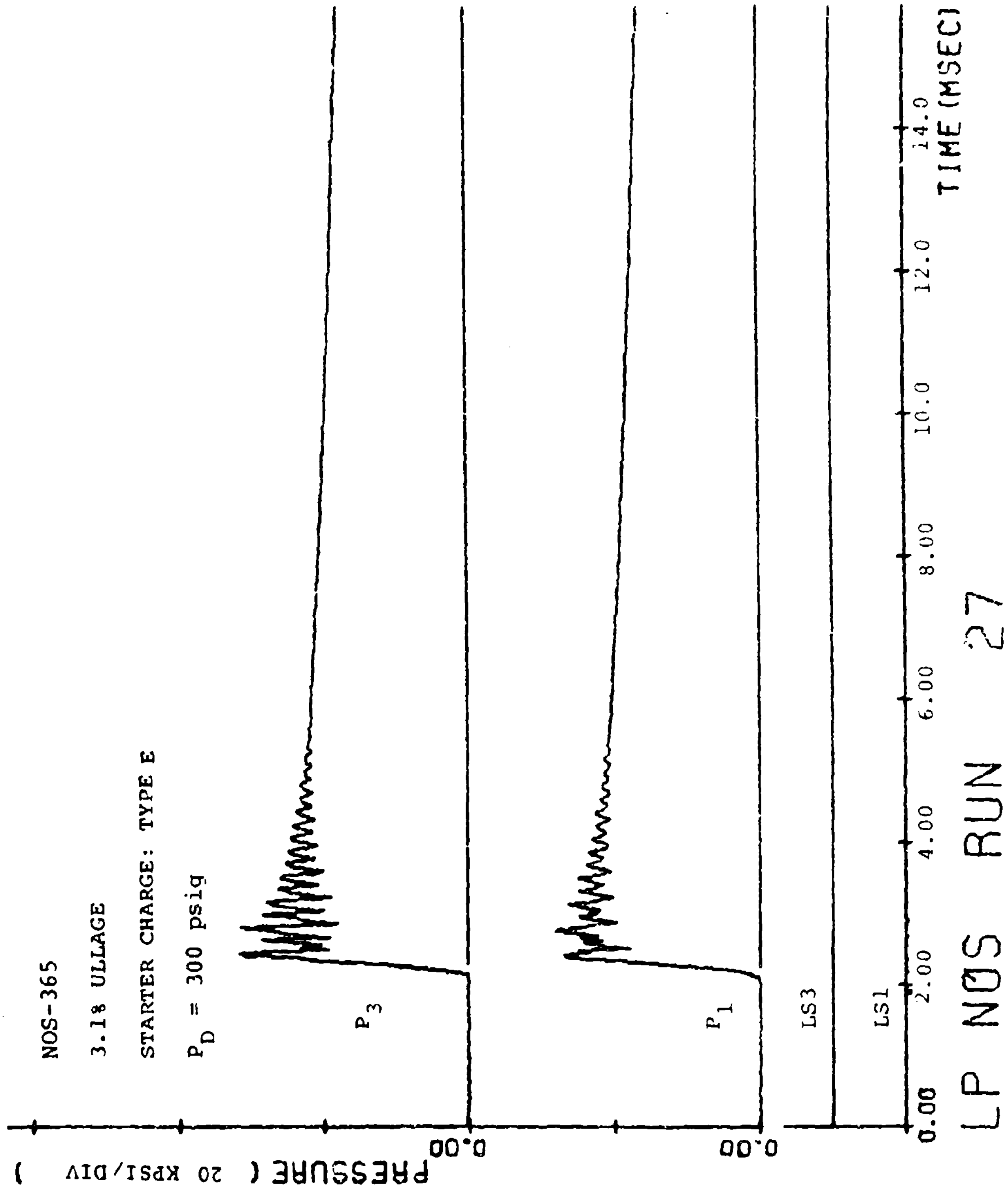


Figure 26. NOS-365 Starter Charge: Type E

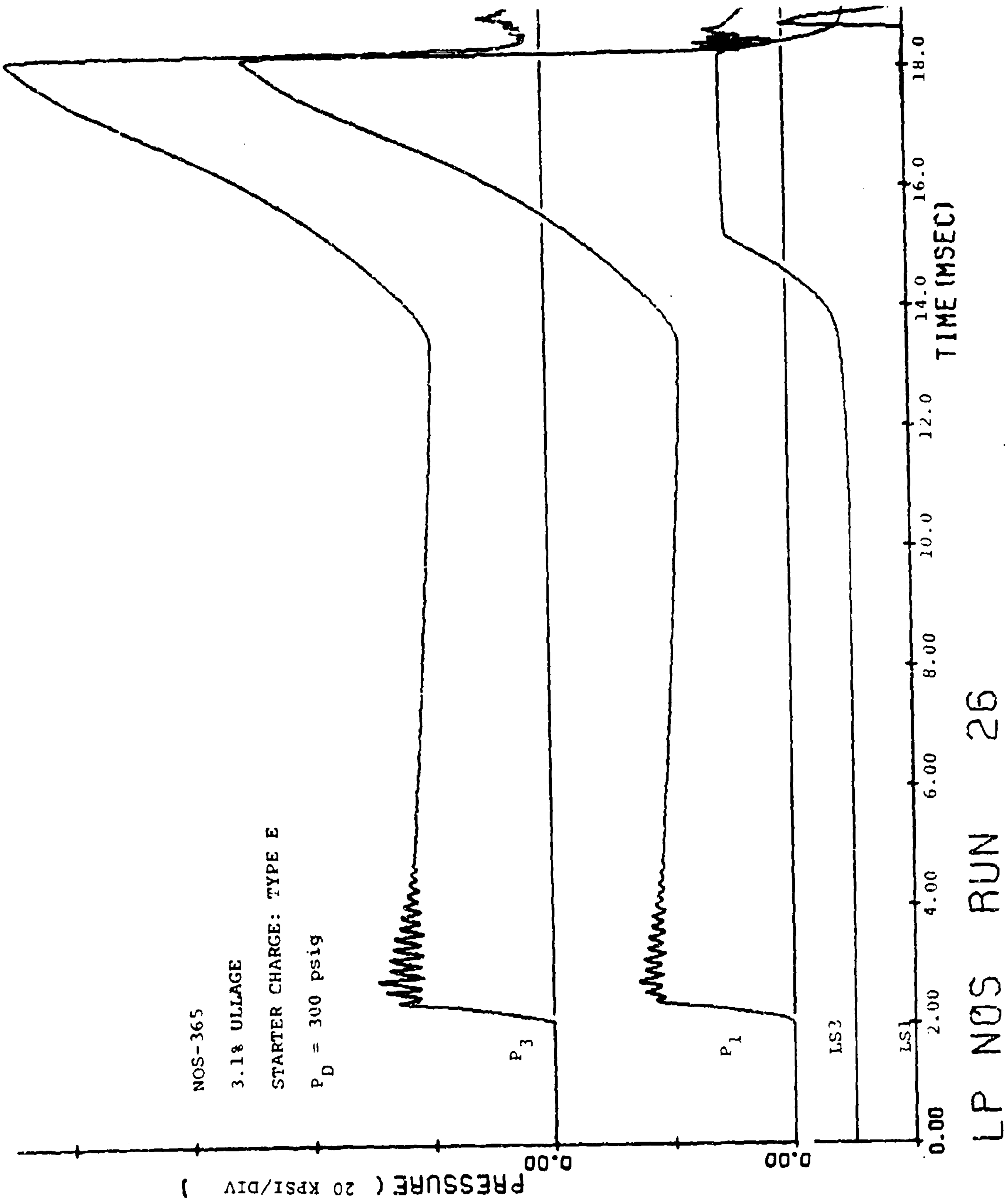


Figure 27. NOS-365 Starter Charge: Type E

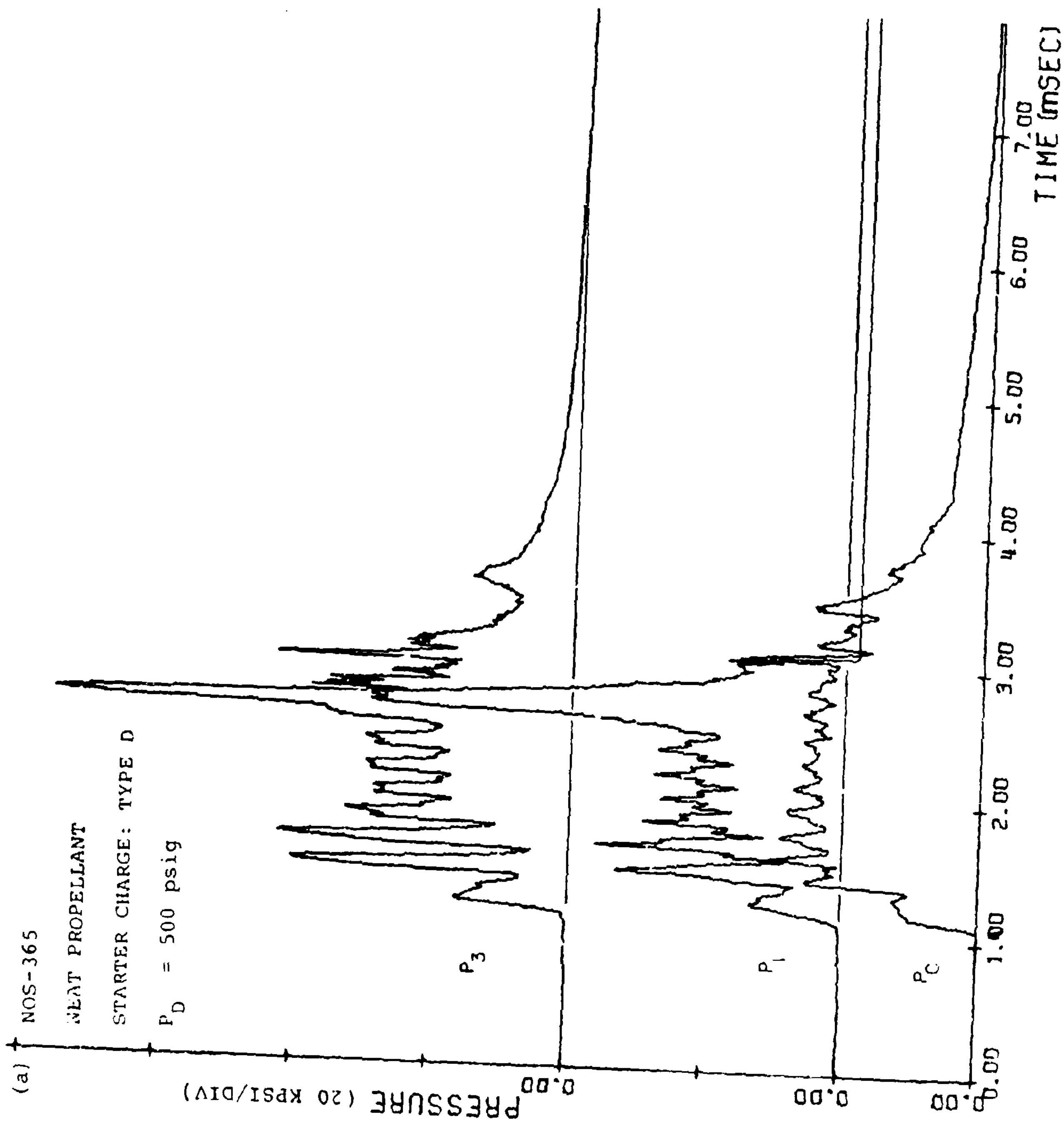


Figure 28. Comparison of Two Neat Propellant Firing Tests with TYPE D Start-Up Curve: (a) Unmodified System with No Pre-pressurization Resulting in Explosive Response; (b) Modified System with Pre-pressurization of 350 psig Resulting in Benign Response.

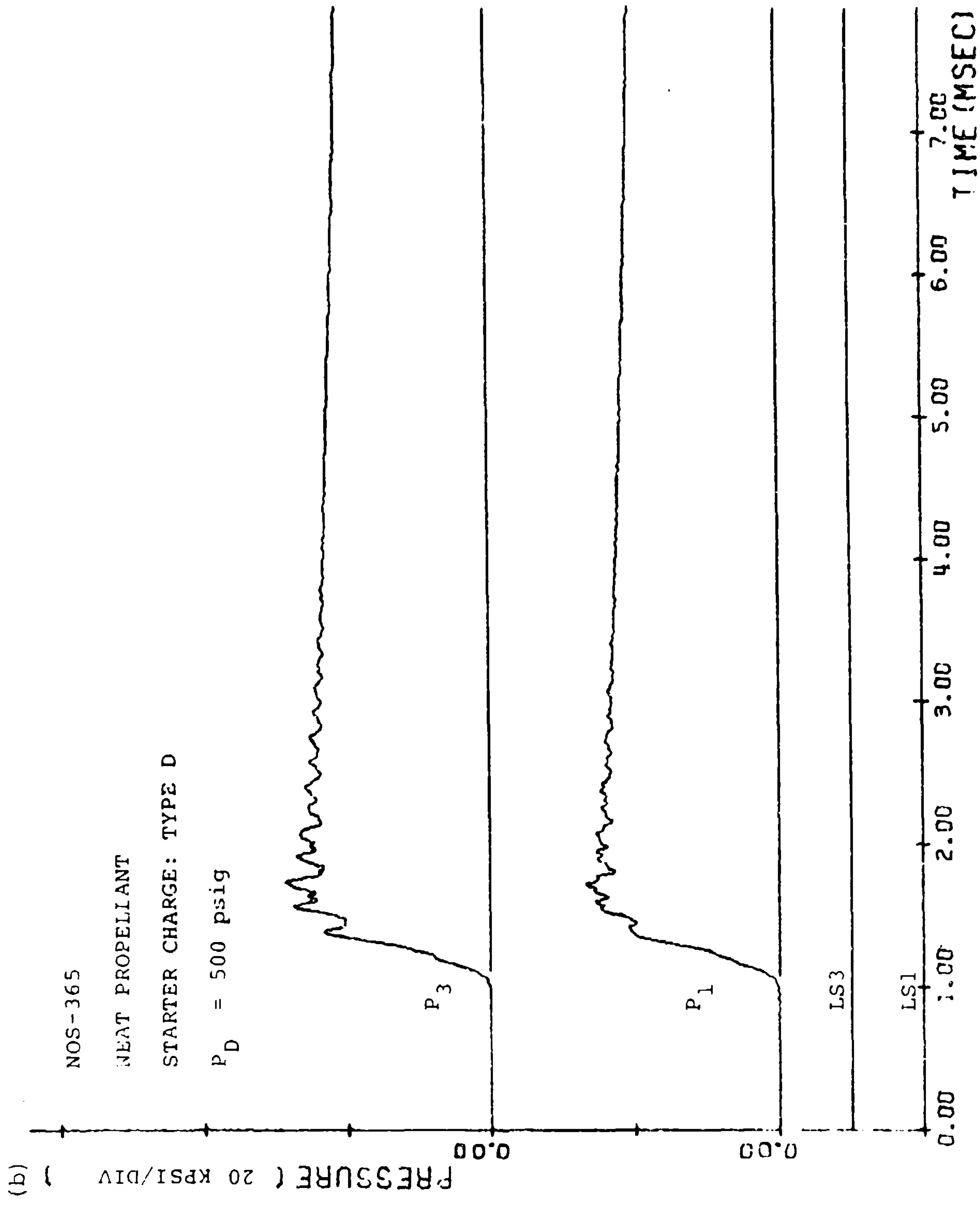


Figure 28. Continued.

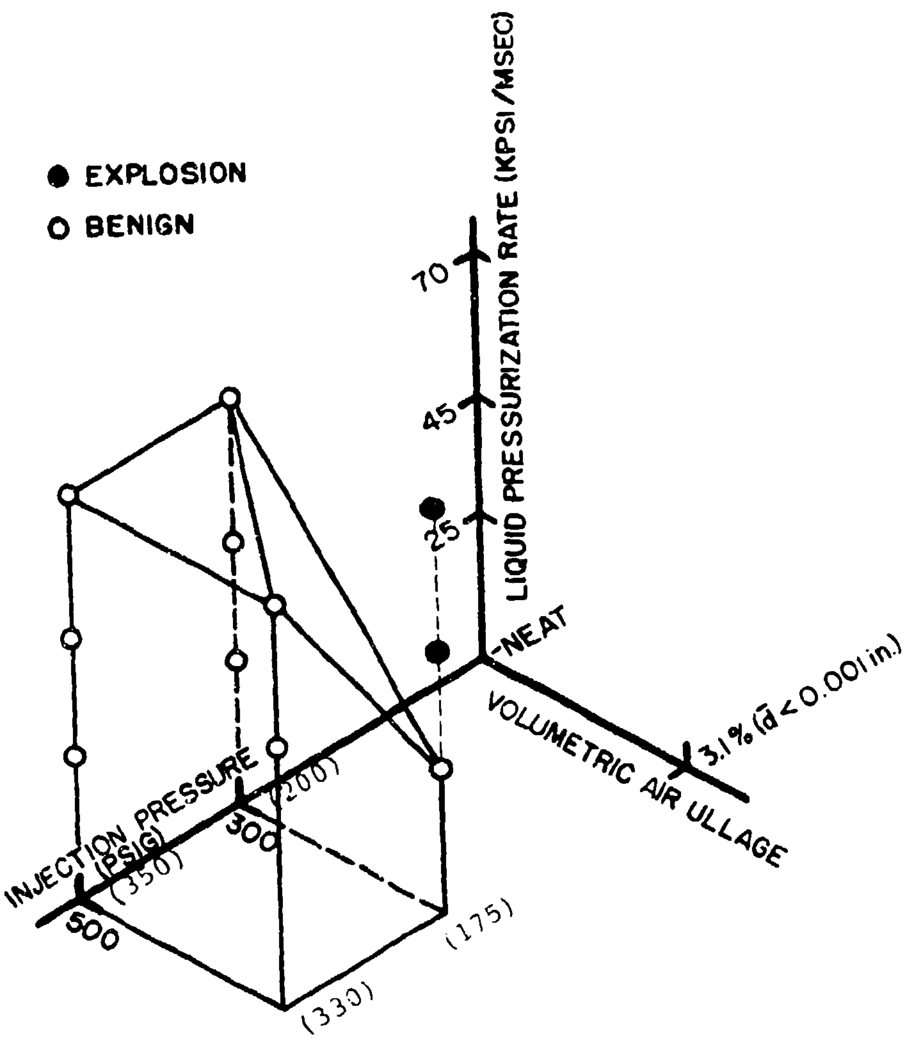


Figure 29. Domain of Safe Operation for Avoidance of Runaway Reaction Due to Compression Ignition of the Liquid Monopropellant.

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